Chapter 2

Thermal –Fluid Sciences

Basic Concepts Of Thermodynamıcs

Objectives

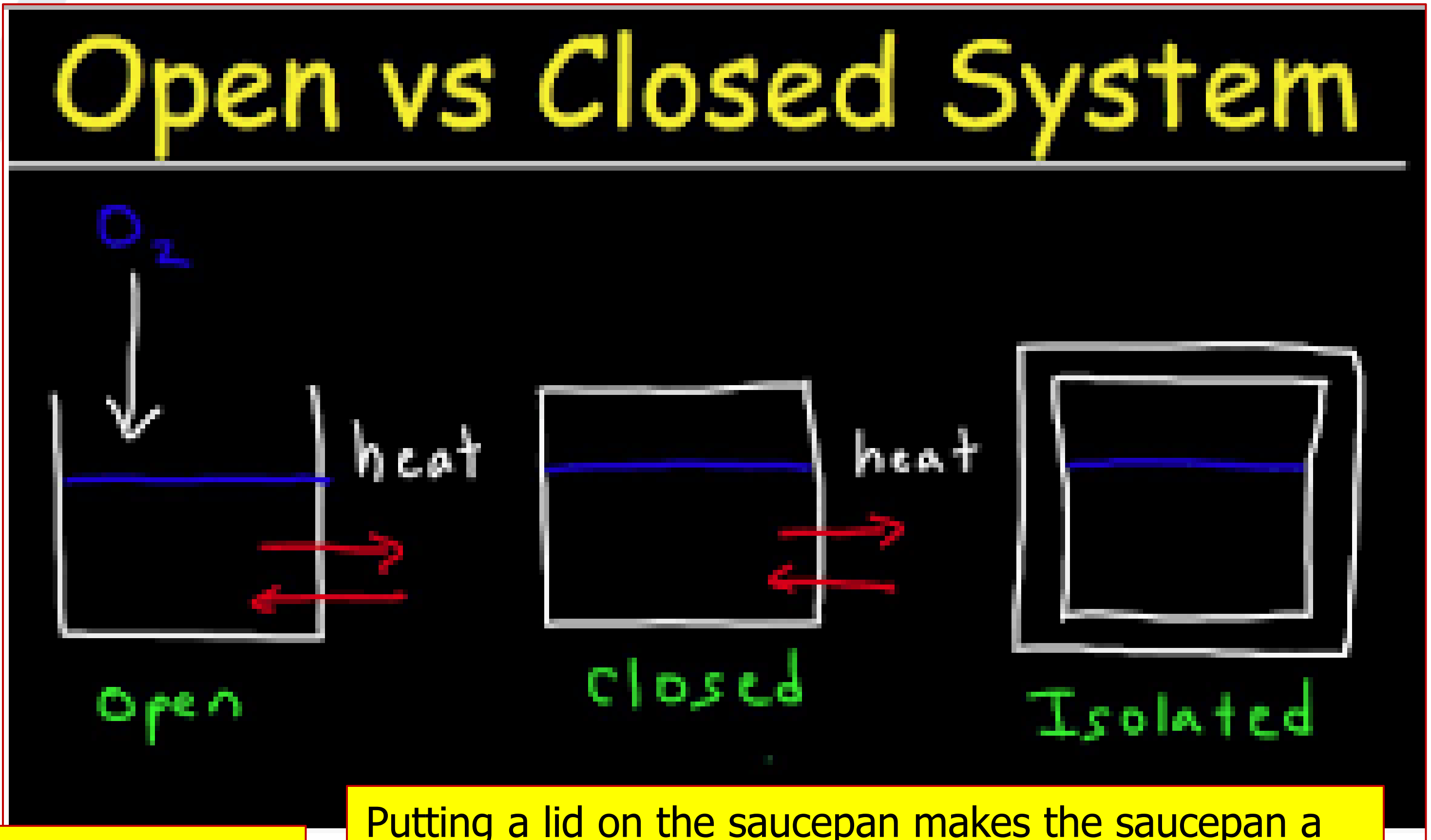
- Identify the unique vocabulary associated with thermodynamics through the precise definition of basic concepts .
- Describe the basic concepts of thermodynamics such as system, state, equilibrium, process, and cycle.
- Discuss properties of a system and define density, specific gravity, and specific weight.
- Review concepts of temperature, temperature scales, pressure, and absolute and gage pressure.

2-1 SYSTEMS AND CONTROL VOLUMES

- **System:** A quantity of matter or a region in space chosen for study.
- **Surroundings:** The mass or region outside the system.
- **Boundary:** The real or imaginary surface that separates the system from its surroundings.
- The boundary of a system can be ***fixed*** or ***movable***.
- Systems may be considered to be ***closed*** or ***open***.
- **Closed system (Control mass):** A fixed amount of mass, and no mass can cross its boundary

An **isolated system does not exchange energy or matter** with its surroundings.

For example, if soup is poured into an insulated container (as seen below) and closed, there is no exchange of heat or matter.



open system is a system that freely
exchanges *energy* and *matter* with its surroundings.

For instance, when you are boiling soup in an open saucepan on a stove, energy and matter are being transferred to the surroundings through steam. T

Putting a lid on the saucepan makes the saucepan a closed system.

A **closed system** is a system that exchanges **only energy** with its surroundings, not matter. By putting a lid on the saucepan, matter can no longer transfer because the lid prevents matter from entering the saucepan and leaving the saucepan. Still, the saucepan allows energy transfer.

The First Law tells us that energy is conserved ...

... but what is **energy** ?

- Energy is the capacity of a body to do work and it can be stored and transferred.
- There are many forms of energy: thermal, mechanical, kinetic, potential, electrical, magnetic, chemical, nuclear and others.
- We will only consider the following three types of energy

1. **Potential Energy**, E_P (External Energy) (Roll the mouse over the gray dashed box.) — Energy associated with the position of the system within a potential field.

2. **Kinetic Energy**, E_K (External Energy) (Roll the mouse over the gray dashed box.) — Energy associated with the net linear or angular velocity of the system.

3. **Internal Energy**, U (Roll the mouse over the gray dashed box.) — Energy associated with the structure and motion of molecules within the system.

What quantities appear in the first law of thermodynamics?

A. force, mass, acceleration
B. inertia, torque, angular momentum
C. work, heat, thermal energy
D. work, heat, entropy

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D. work, heat, entropy
E. enthalpy, entropy, heat

What was the original unit for measuring heat?

A. BTU
B. Watt
C. Joule
D. Pascal
E. Calorie

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A. Isochoric
B. Isentropic
C. Isothermal
D. Isobaric
E. Adiabatic

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Heat is

A. the amount of thermal energy in an object.
B. the energy that moves from a hotter object to a colder object.
C. a fluid-like substance that flows from a hotter object to a colder object.
D. both A and B.
E. both B and C.

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B. heat constant.
C. specific heat.
D. thermal index.

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2-1 SYSTEMS AND CONTROL VOLUMES-1

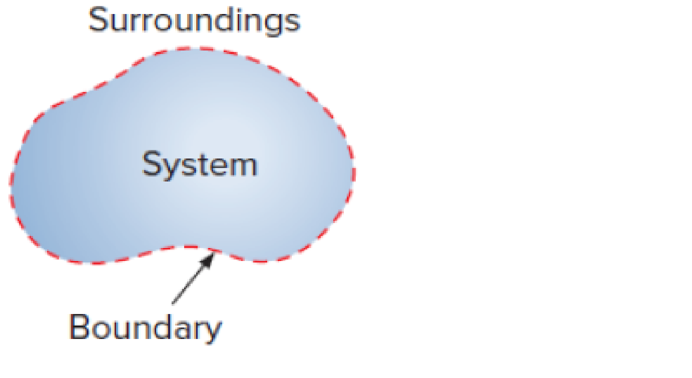


FIGURE 2-1

System, surroundings, and boundary.

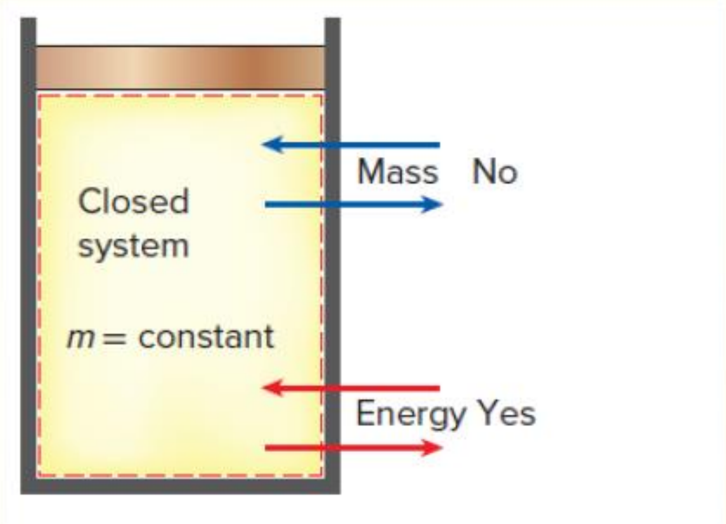


FIGURE 2-2

Mass cannot cross the boundaries of a closed system, but energy can.

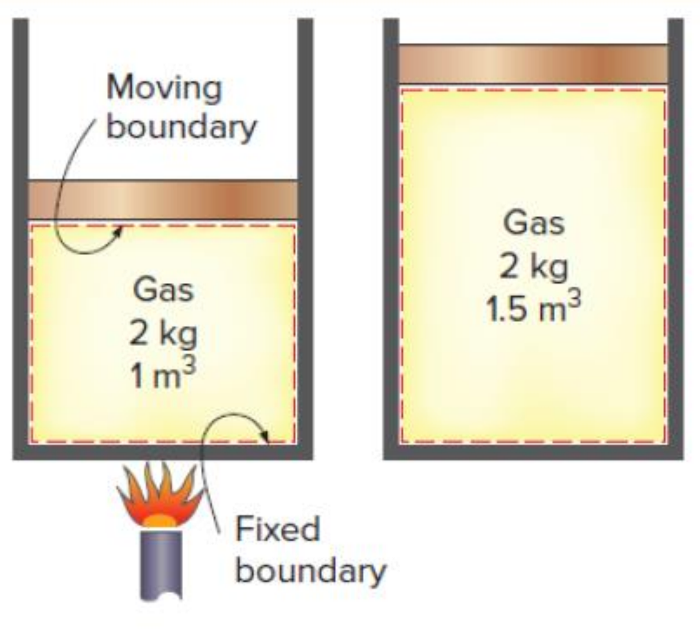


FIGURE 2-3

A closed system with a moving boundary.

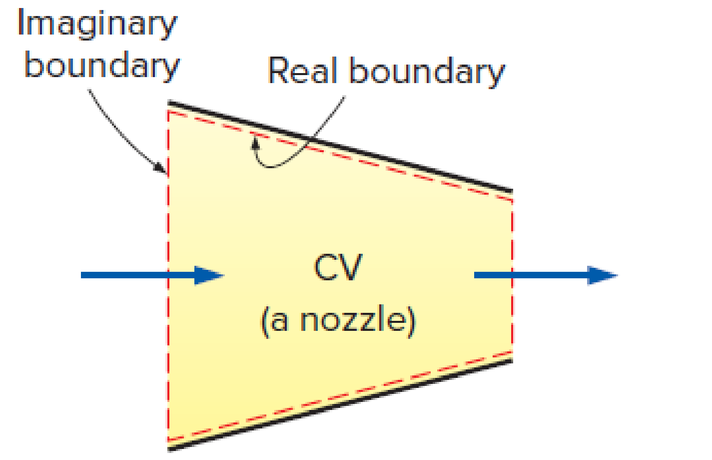
2-1 SYSTEMS AND CONTROL VOLUMES-2

- **Open system (control volume):** A properly selected region in space.
- It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle.
- Both mass and energy can cross the boundary of a control volume.
- **Control surface:** The boundaries of a control volume. It can be real or imaginary.

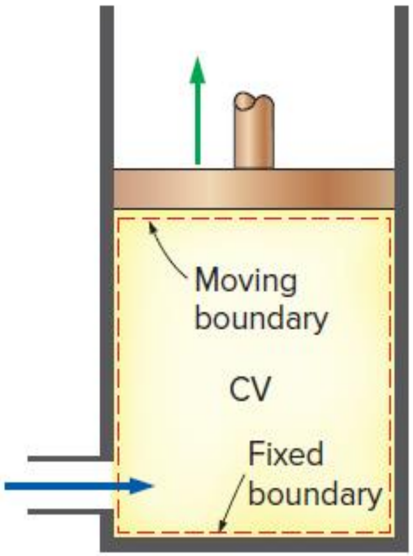
FIGURE 2-5

An open system (a control volume) with a moving boundary.

A control volume can involve fixed, moving, real, and imaginary boundaries.



(a) A control volume (CV) with real and imaginary boundaries



(b) A control volume (CV) with fixed and moving boundaries as well as real and imaginary boundaries

2-2 PROPERTIES OF A SYSTEM

- **Property:** Any characteristic of a system.
- Some familiar properties are pressure *P*, temperature *T*, volume *V*, and mass *m*.
- Properties are considered to be either *intensive* or *extensive*.

Summary.

An extensive property is a property that depends on the amount of matter in a sample. Mass and volume are examples of extensive properties.

An intensive property is a property of matter that depends only on the type of matter in a sample and not on the amount.

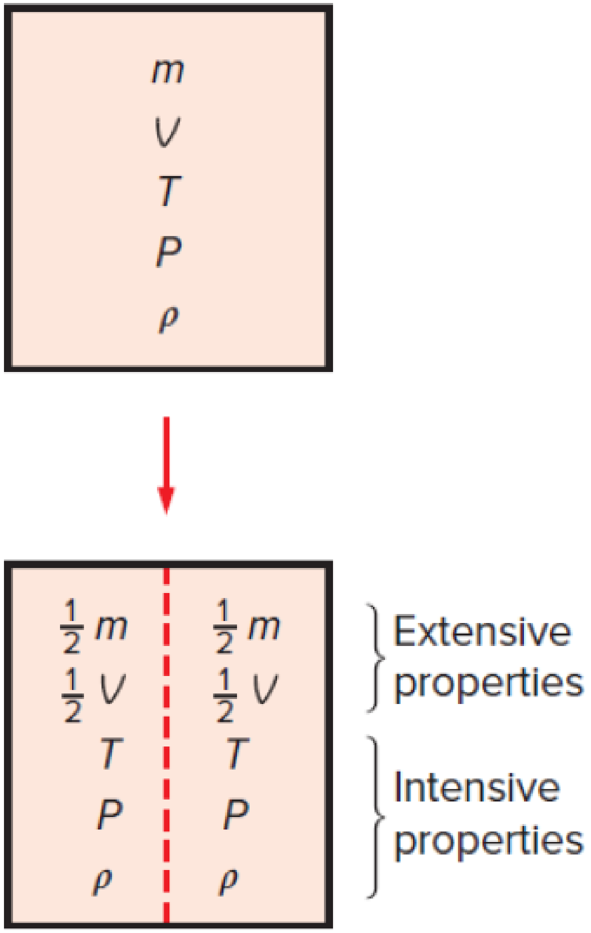


FIGURE 2-6
Criterion to differentiate intensive and extensive properties.

2-2 PROPERTIES OF A SYSTEM

- **Intensive properties:** Those that are independent of the mass of a system, such as temperature, pressure, and density.
- **Extensive properties:** Those whose values depend on the size—or extent—of the system.
- **Specific properties:** Extensive properties per unit mass.

Extensive properties per unit mass are called specific properties; examples; specific volume and specific energy.

$$(v = V/m)$$

$$(e = E/m)$$

- Property is a particular characteristic of a given system
  - Extensive properties are dependent on the amount of mass in the system (m, V, U, etc.)
  - Intensive properties are not dependent on the amount of mass in the system (P, T, etc.)
  - Specific properties are extensive properties per unit mass and indicated by lower case letters (v = V/m, u = U/m, etc.)
  - Divide the system into smaller parts to determine extensive or intensive
  - State is defined using a set of properties

Comparison Chart

	Intensive Property	Extensive Property
Depends Upon	An intensive property is a system of properties that does not depend on the amount or size of the material.	The extensive property is a system of properties that depends on the amount or size of the material.
Constant	Intensive properties remain constant.	Extensive properties are not constant.
Varies	Intensive properties do not change with the change in amount or size of the material.	Extensive properties always change with the change in amount or size of the material.
Result	Intensive properties show the same result in different samples test.	Extensive properties show the variable result in the different samples test.
Example	Intensive properties are, boiling point, color, the state of matter, density, odor, melting point, hardness, malleability.	extensive properties include, mass, volume, length, height etc.

General Principles

Energy

Thermal energy E_{th} Microscopic energy of moving molecules and stretched molecular bonds. ΔE_{th} depends on the initial/final states but is independent of the process.

Work W Energy transferred to the system by forces in a mechanical interaction.

Heat Q Energy transferred to the system via atomic-level collisions when there is a temperature difference. A thermal interaction.

Continuum

- Matter is made up of atoms that are widely spaced in the gas phase. Yet it is very convenient to disregard the atomic nature of a substance and view it as a continuous, homogeneous matter with no holes, that is, a **continuum**.

- The continuum allows us to treat properties as point functions and to assume the properties vary continually in space with no jump in discontinuities.

Continuum

- This idealization is valid as long as the size of the system we deal with is large relative to the space between the molecules.
- This is the case in practically all problems.
- In this course will limit our consideration to substances that can be modeled as a continuum.

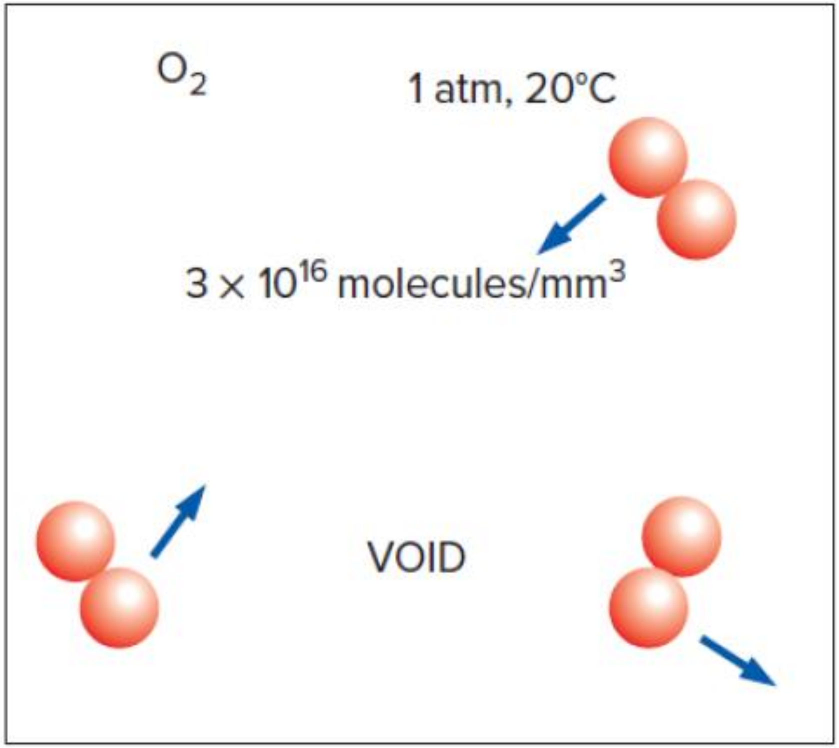


FIGURE 2-7
Despite the relatively large gaps between molecules, a gas can usually be treated as a continuum because of the very large number of molecules even in an extremely small volume.

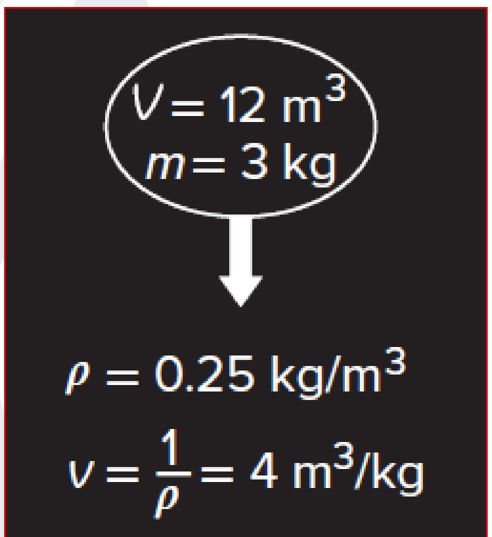
2-3 DENSITY AND SPECIFIC GRAVITY

Density

$$\rho = \frac{m}{V} \qquad (kg/m^3)$$

Specific volume

$$v = \frac{V}{m} = \frac{1}{\rho}$$



Specific gravity: The ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C).

$$SG = \frac{\rho}{\rho_{H_2O}}$$

Specific weight: The weight of a unit volume of a substance.

$$\gamma_s = \rho g \qquad (\mathrm{N/m^3})$$

Density is mass per unit volume; specific volume is volume per unit mass.

TABLE 2-1 Specific gravities of some substances at 0°C

Substance	SG
Water	1.0
Blood	1.05
Seawater	1.025
Gasoline	0.7
Ethyl alcohol	0.79
Mercury	13.6
Wood	0.3-0.9
Gold	19.2
Bones	1.7-2.0
Ice	0.92
Air(at 1 atm)	0.0013

2-4 STATE AND EQUILIBRIUM

- Thermodynamics deals with *equilibrium* states.
- Equilibrium: A state of balance.
- In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- Thermal equilibrium: If the temperature is the same throughout the entire system.

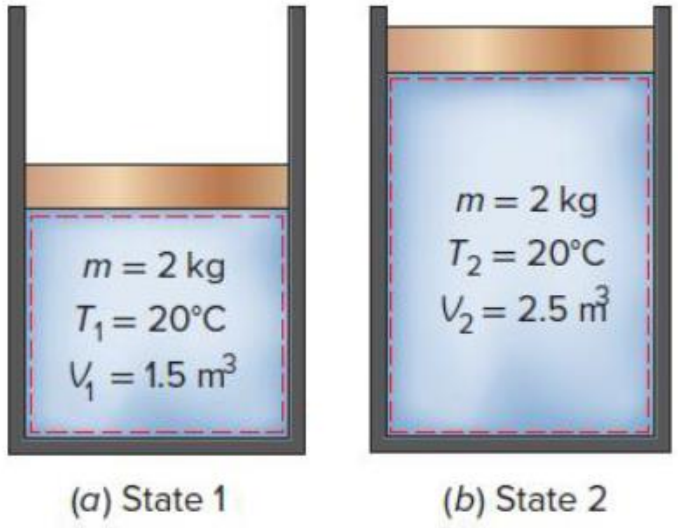


Figure 2-9: A system at two different states.

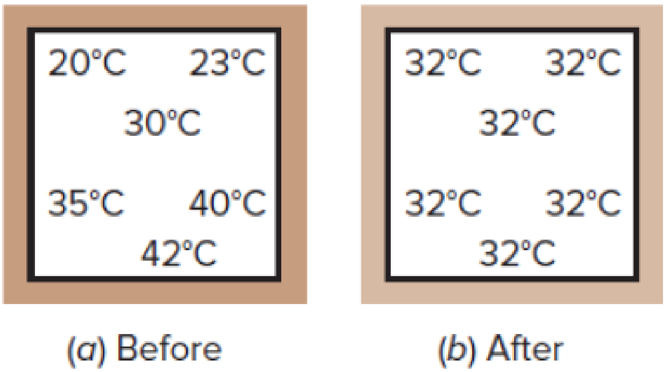
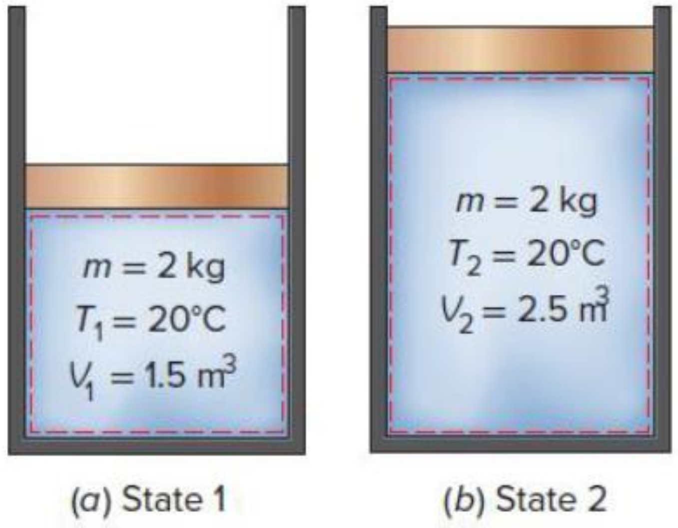


FIGURE 2-10

A closed system reading thermal equilibrium.

2-4 STATE AND EQUILIBRIUM

- **Mechanical equilibrium:** If there is no change in pressure at any point of the system with time.
- **Phase equilibrium:** If a system involves two phases and when the mass of each phase reaches an equilibrium level and stays there.
- **Chemical equilibrium:** If the chemical composition of a system does not change with time, that is, no chemical reactions occur.



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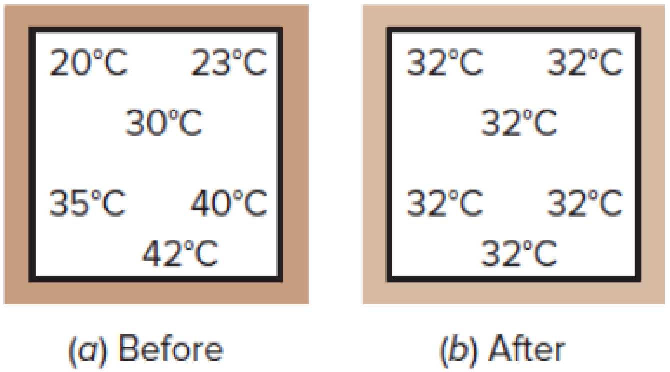


FIGURE 2-10

A closed system reading thermal equilibrium.

2-5 PROCESSES AND CYCLES

Process: **Any change that a system undergoes from one equilibrium state to another.**

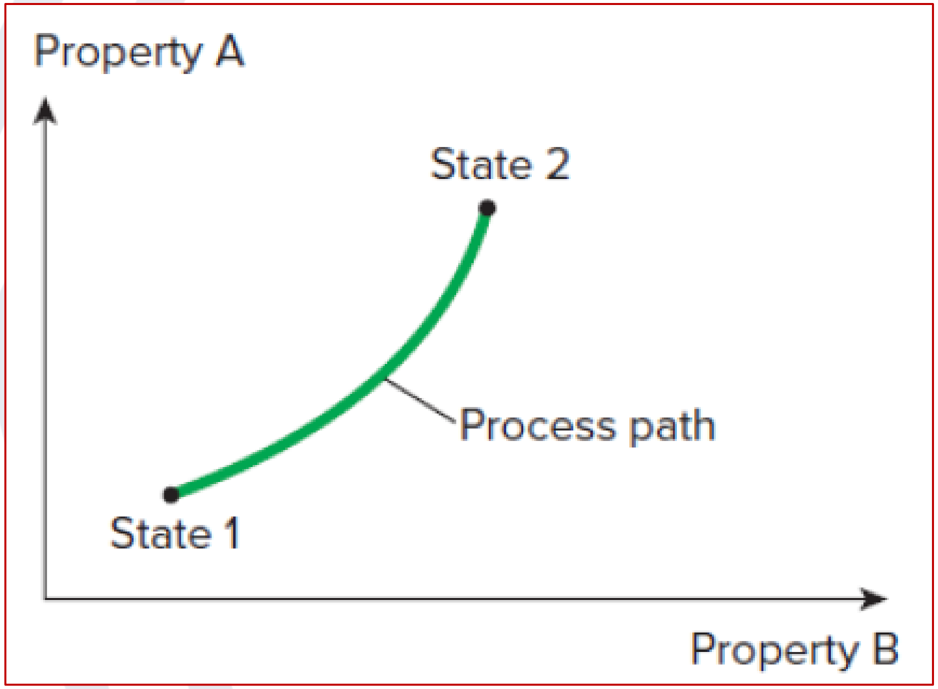
of states through which a system passes during a process.

To describe a process completely, one should specify the initial and final states, as well as the path it follows, and the interactions with the surroundings.

Quasistatic or quasi-equilibrium process: **When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times.**

2-5 PROCESSES AND CYCLES

FIGURE 2-12
A process between states 1 and 2 and the process path.



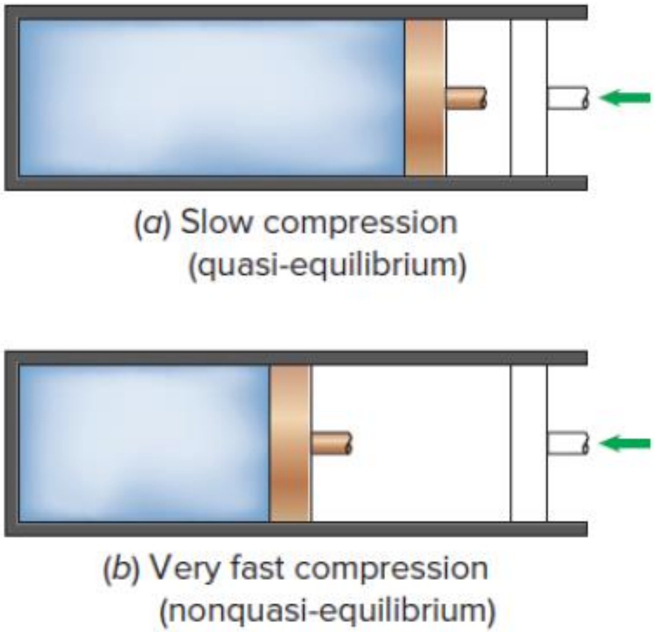


FIGURE 2-13
Quasi-equilibrium and nonquasi-equilibrium compression processes.

2-5 PROCESSES AND CYCLES-1

- Process diagrams plotted by employing thermodynamic properties as coordinates are very useful in visualizing the processes.
- Some common properties that are used as coordinates are temperature *T*, pressure *P*, and volume *V* (or specific volume *v*).
- The prefix *iso-* is often used to designate a process for which a particular property remains constant.

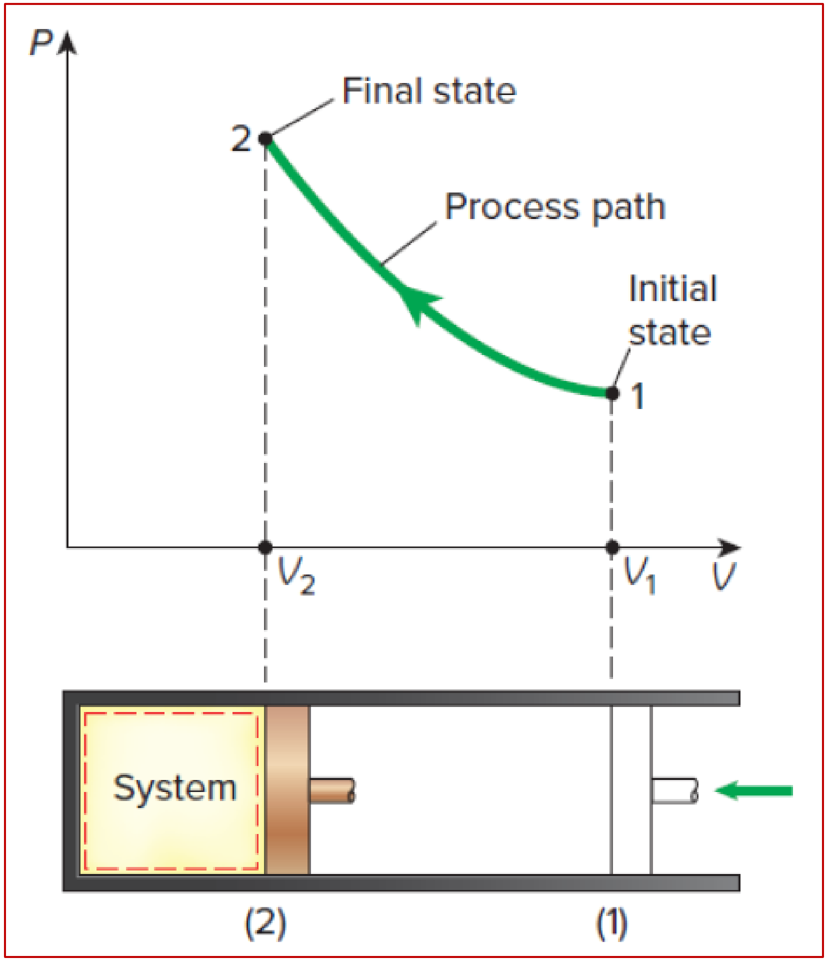


FIGURE 2-14
The P-V diagram of a compression process.

2-5 PROCESSES AND CYCLES-1

- **Isothermal process:** A process during which the temperature *T* remains constant.
- **Isobaric process:** A process during which the pressure *P* remains constant.
- **Isochoric (or isometric) process:** A process during which the specific volume *v* remains constant.
- **Cycle:** A process during which the initial and final states are identical.

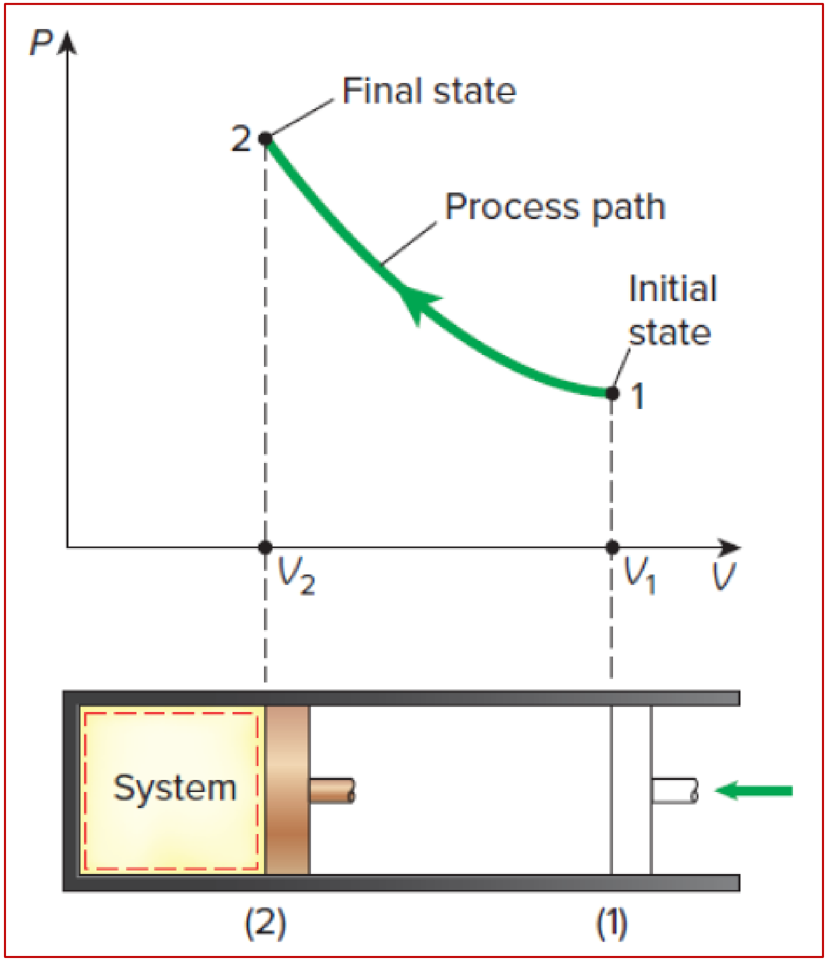
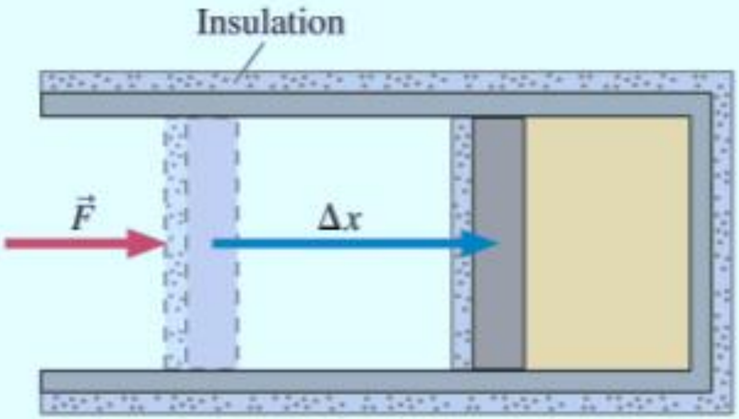


FIGURE 2-14
The P-V diagram of a compression process.

A gas cylinder and piston are covered with heavy insulation. The piston is pushed into the cylinder, compressing the gas. In this process, the gas temperature



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B. increases.
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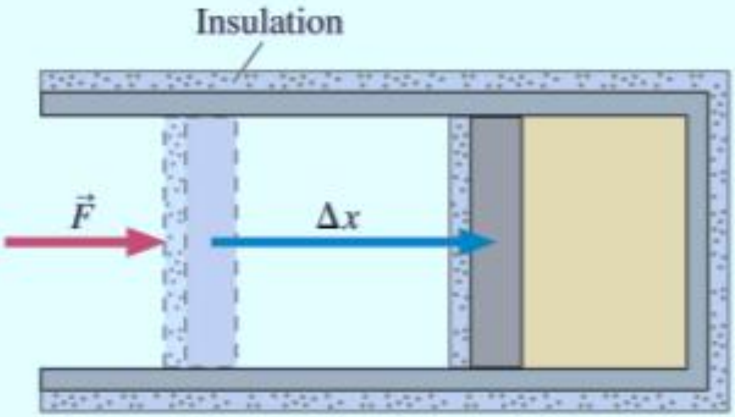

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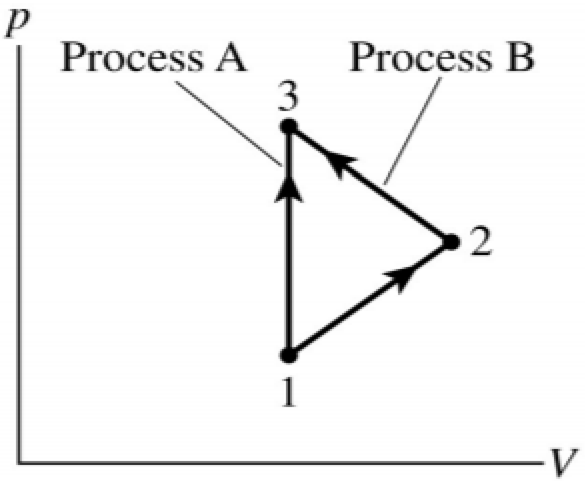
Two process are shown that take an ideal gas from state 1 to state 3. Compare the work done by process A to the work done by process B.



A. $W_A > W_B$
B. $W_A < W_B$
C. $W_A = W_B = 0$
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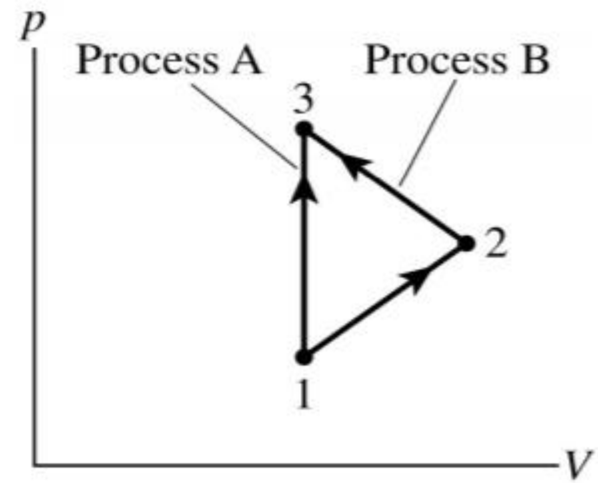

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Which of the following processes involve heat?

A. The brakes in your car get hot when you stop.
B. You push a rigid cylinder of gas across a frictionless surface.
C. A steel block is placed under a candle.
D. You push a piston into a cylinder of gas, increasing the temperature of the gas.

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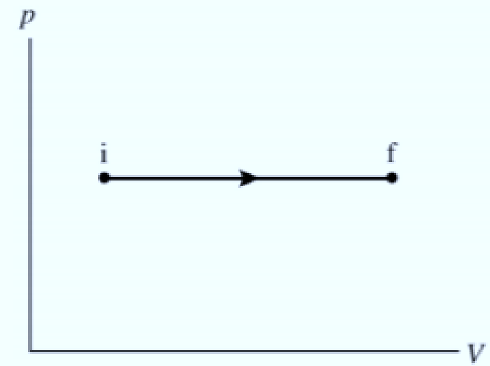

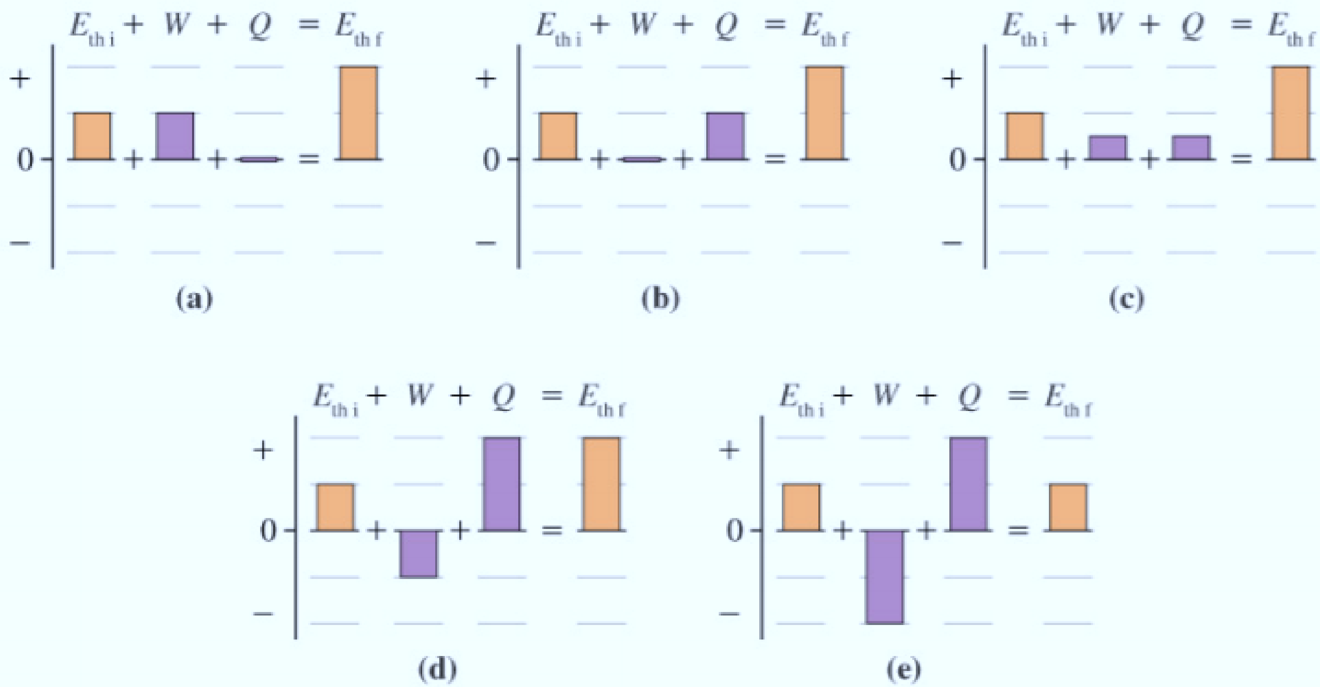

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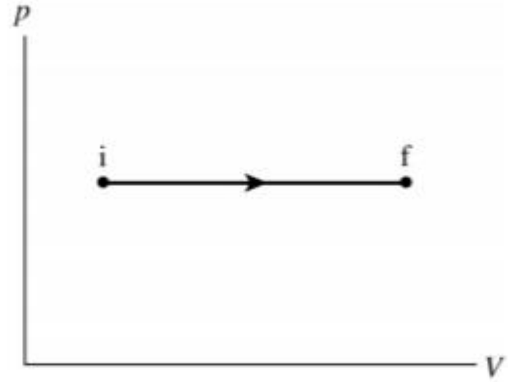

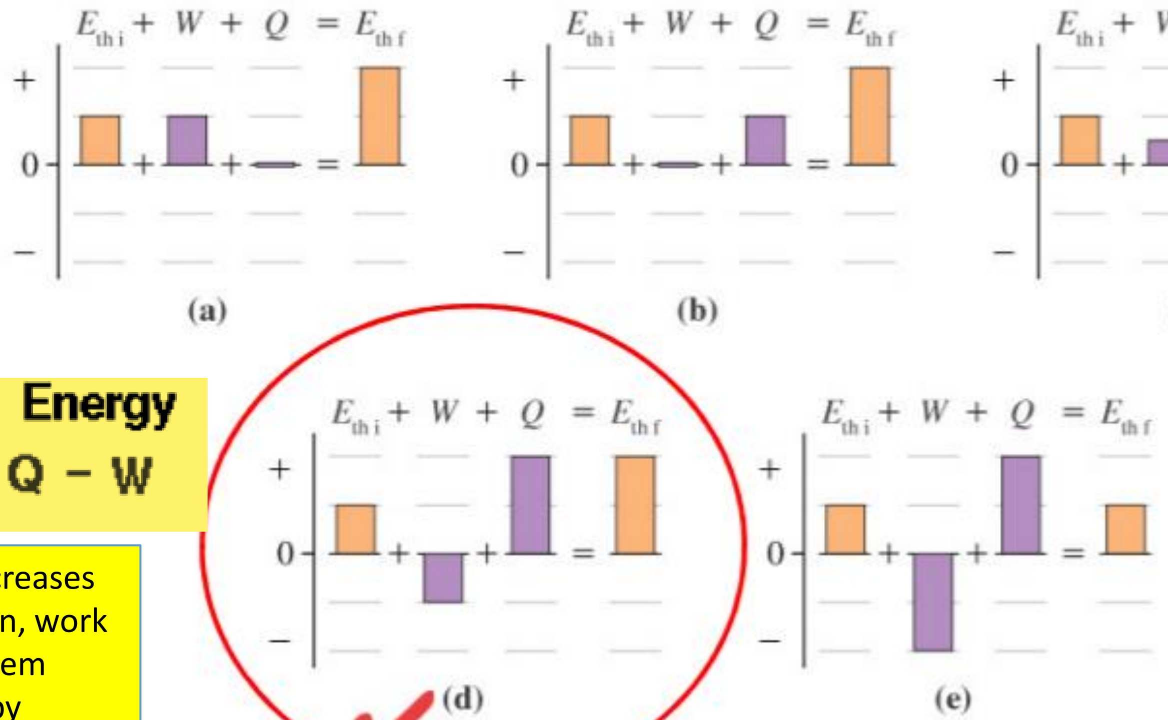

E = Internal Energy

$$E_2 - E_1 = Q - W$$

Internal energy increases due to compression, work is done on the system which is negative by convention

First law of thermodynamics / Formula

$$\Delta U = Q - W$$

ΔU = change in internal energy

Q = heat added

W = work done by the system

From the web

The first law of thermodynamics states that the change in **internal energy** of a system equals the net heat transfer into the system minus the net work done by the system. In equation form, the first law of thermodynamics is $\Delta U = Q - W$. Here ΔU is the change in **internal energy** U of the system.

Suppose you are an astronaut in space, hard at work in your sealed spacesuit. The only way that you can transfer excess heat to the environment is by

A. conduction

B. radiation

C. convection

D. evaporation

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The Steady-Flow Process

- The term steady implies no change with time. The opposite of steady is unsteady, or transient.
- A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as steady-flow devices.
- Steady-flow process: A process during which a fluid flows through a control volume steadily.

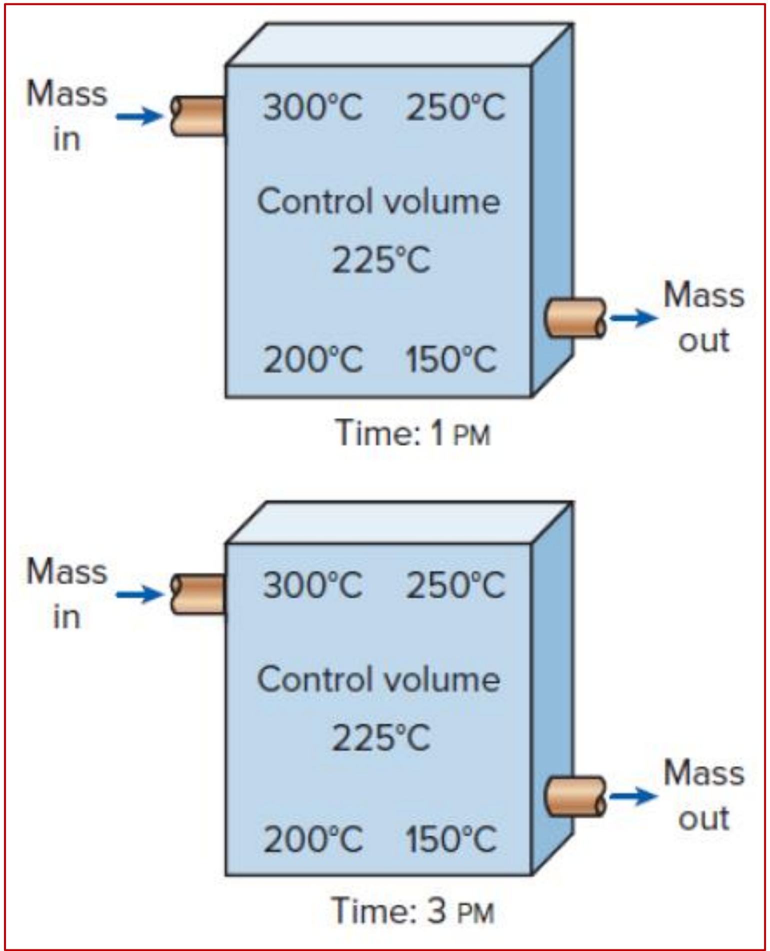

FIGURE 2-15

During a steady-flow process, fluid properties within the control volume may change with position but not with time.

The Steady-Flow Process

- Steady-flow conditions can be closely approximated by devices that are intended for continuous operation such as **turbines, pumps, boilers, condensers, and heat exchangers or power plants or refrigeration systems.**

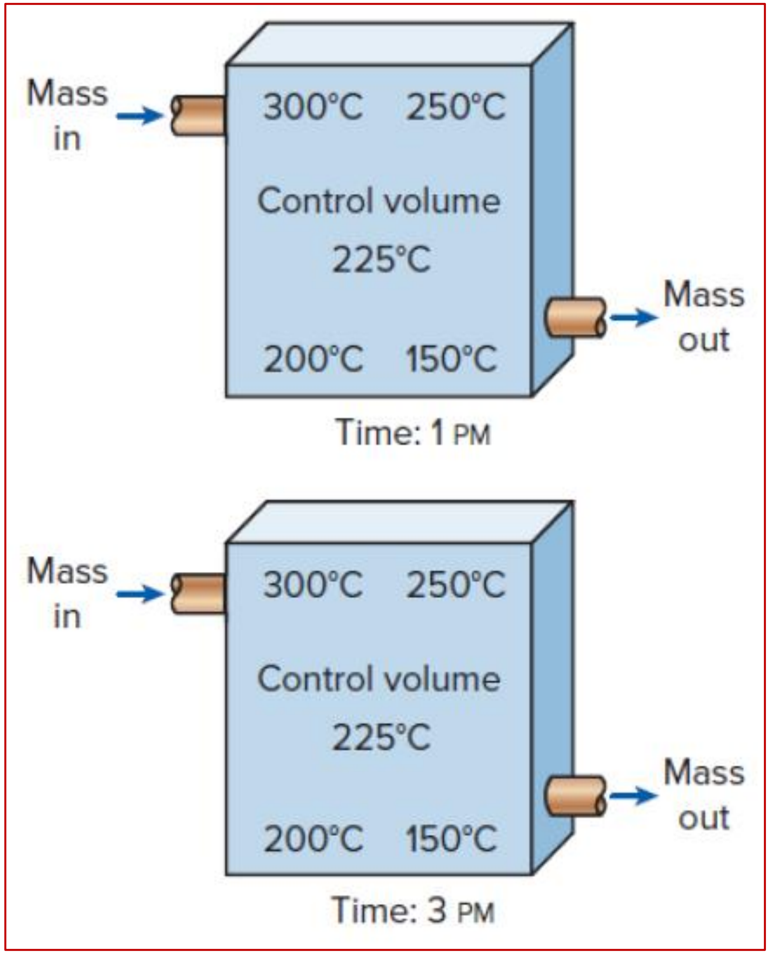

FIGURE 2-15
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The Steady-Flow Process-1

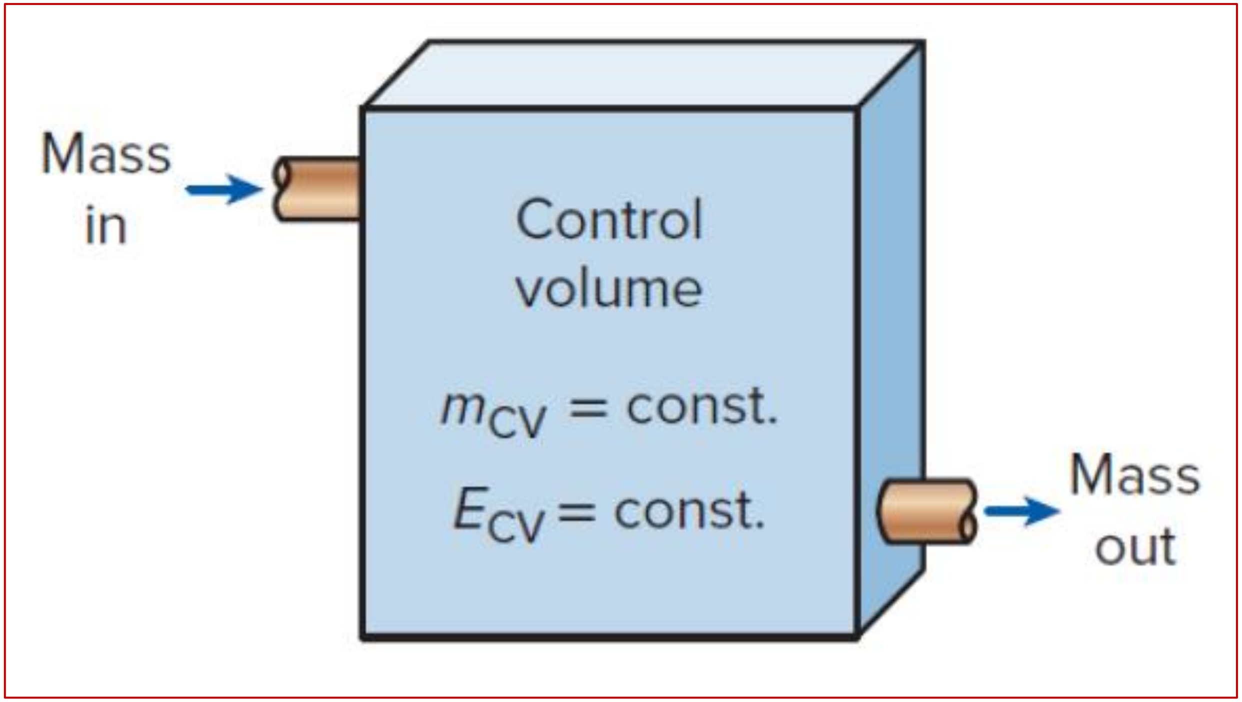


FIGURE 2-16
Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

2-6 Temperature And The Zeroth Law Of Thermodynamics

- **The zeroth law of thermodynamics: If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.**
- **By replacing the third body with a thermometer, the zeroth law can be restated as *two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact*.**

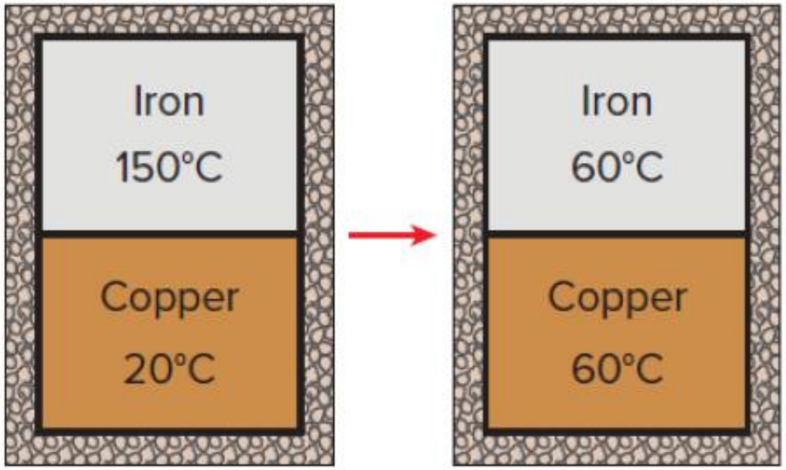


FIGURE 2-17

Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure.

Temperature Scales

- All temperature scales are based on some easily reproducible states such as the freezing and boiling points of water: the *ice point* and the *steam point.*
- Ice point: A mixture of ice and water that is in equilibrium with air saturated with vapor at 1 atm pressure (0°C or 32°F).
- Steam point: A mixture of liquid water and water vapor (with no air) in equilibrium at 1 atm pressure (100°C or 212°F).
- Celsius scale: in SI unit system

Temperature Scales

- Fahrenheit scale: in English unit system
- Thermodynamic temperature scale: A temperature scale that is independent of the properties of any substance.
- Kelvin scale (SI) Rankine scale (English)
- A temperature scale nearly identical to the Kelvin scale is the ideal-gas temperature scale. The temperatures on this scale are measured using a constant-volume gas thermometer.

Temperature Scales-1

- The temperature scales used in the SI and in the English system today are the **Celsius scale** (formerly called the *centigrade scale;* in 1948 it was renamed after the **Swedish astronomer A. Celsius, 1702–1744,** who devised it).
- On the Celsius scale, the ice and steam points were originally assigned the values of 0 and 100°C, respectively.
- The **Fahrenheit scale** (named after the German instrument maker **G. Fahrenheit**, 1686–1736).
- The corresponding values on the Fahrenheit scale are 32 and 212°F. These are often referred to as ***two-point scales*** **since temperature values are assigned at two different po**ints.

Temperature Scales-1

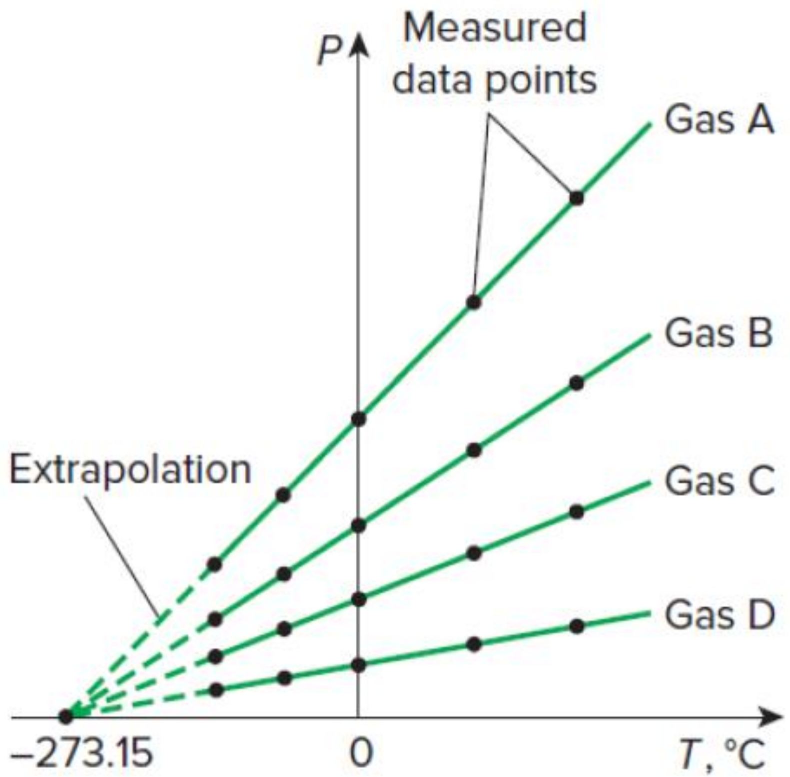


FIGURE 2-18
P **versus** ***T*** **plots of the experimental data obtained from a constant-volume gas thermometer using four different gases at different(but low) pressures.**

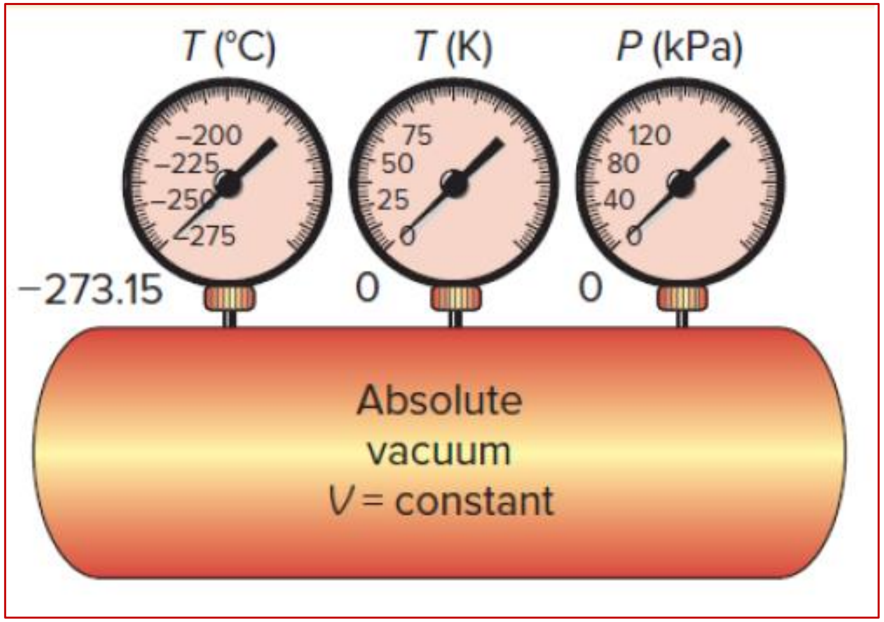


FIGURE 2-19

A constant-volume gas thermometer would read $-273.15°\mathrm{C}$ at absolute zero pressure.

https://www.youtube.com/watch?v=zIeLBRShqVA

Temperature Scales

Temperature Scales-2

$$T(K) = T(°C) + \mathbf{273.15}$$

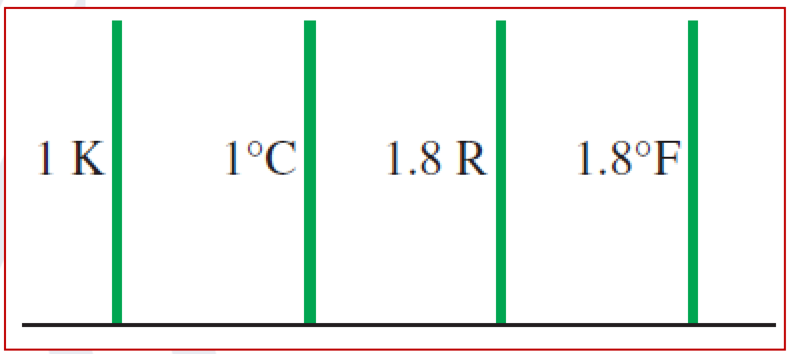
$$T(\boldsymbol{R}) = T(°\boldsymbol{F}) + 459.67$$

$$T(\mathrm{R}) = 1.8T(K)$$

$$T(°\mathrm{F}) = 1.8T(°C) + 32$$

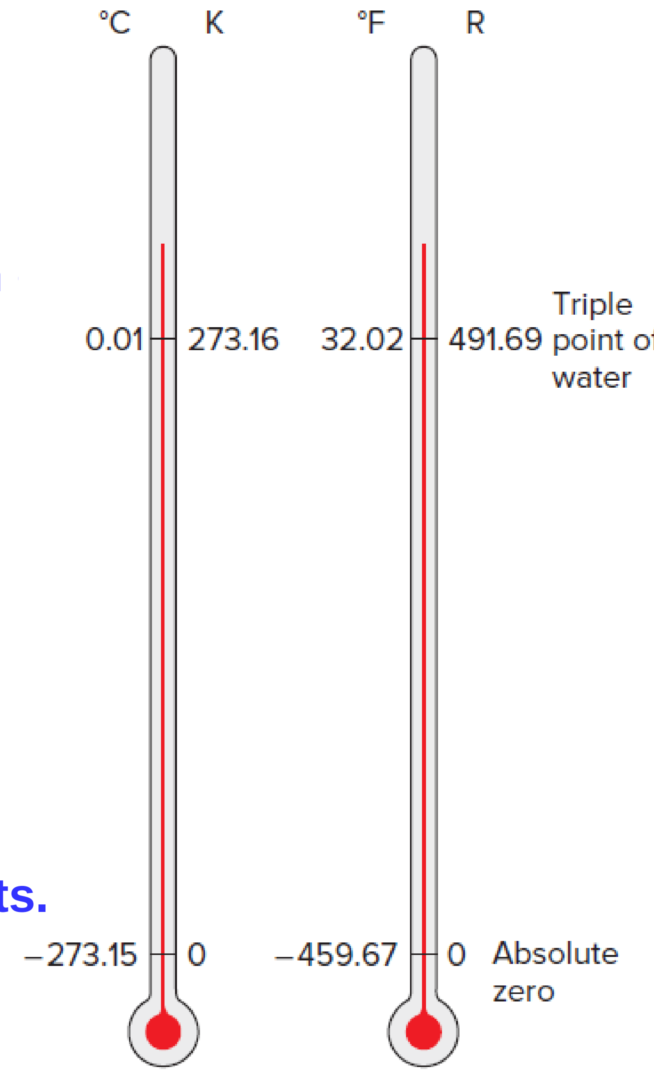
$$\Delta T(\mathrm{K}) = \Delta T(°\mathrm{C})$$

$$\Delta T(\mathrm{R}) = \Delta T(°\mathrm{F})$$



Comparison of magnitudes of various temperature units.

Comparison temperature scales.



- **The reference temperature in the original Kelvin scale was the *ice point*, 273.15 K, which is the temperature at which water freezes (or ice melts).**
- **The reference point was changed to a much more precisely reproducible point, the *triple point* of water (the state at which all three phases of water coexist in equilibrium), which is assigned the value 273.16 K.**

Conversion Formulas

- **Celsius From Kelvin:** [*C*] = [*K*] - 273.15
- **Kelvin from Celsius:** [*K*] = [*C*] + 273.15
- **Fahrenheit from Kelvin:** [*F*] = [*K*] 9/5 - 459.67
- **Kelvin from Fahrenheit:** [*K*] = ([*F*] + 459.67) 5/9
- **Fahrenheit from Celsius:** [*F*] = [*C*] 9/5 + 32
- **Celsius from Fahrenheit:** [*C*] = ([*F*] - 32) 5/9
- **Rankine from Kelvin:** [*R*] = [*K*] 9/5
- **Kelvin from Rankine:** [*K*] = [*R*] 5/9

EXAMPLE 2–1 Expressing Temperature Rise in Different Units

During a heating process, the temperature of a system rises by 10°C. Express this rise in temperature in K, °F, and R.

SOLUTION

The temperature rise of a system is to be expressed in different units.

Analysis

This problem deals with temperature changes, which are identical in Kelvin and Celsius scales. Then,

$$\Delta T(\mathrm{K}) = \Delta T(^\circ\mathrm{C}) = \mathbf{10\ K}$$

The temperature changes in Fahrenheit and Rankine scales are also identical and are related to the changes in Celsius and Kelvin scales through **Eqs. 2–8** and **2–11**:

$$\Delta T(\mathrm{R}) = 1.8\ \Delta T(\mathrm{K}) = (1.8)(10) = \mathbf{18\ R}$$

and

$$\Delta T(^\circ\mathrm{F}) = \Delta T(\mathrm{R}) = \mathbf{18^\circ F}$$

Discussion

Note that the units °C and K are interchangeable when dealing with temperature differences.

2-7 PRESSURE

Pressure: **A normal force exerted by a fluid per unit area.**

$$1 \text{ Pa} = 1 \text{ N/m}^2$$

$$1 \text{ bar} = 10^5 \text{ Pa} = 0.1 \text{ MPa} = 100 \text{ kPa}$$
$$1 \text{ atm} = 101{,}325 \text{ Pa} = 101.325 \text{ kPa} = 1.01325 \text{ bars}$$
$$1 \text{ kgf/cm}^2 = 9.807 \text{ N/cm}^2 = 9.807 \times 10^4 \text{ N/m}^2 = 9.807 \times 10^4 \text{Pa}$$
$$= 0.9807 \text{ bar}$$
$$= 0.9807 \text{ atm}$$

Some basic pressure gages.

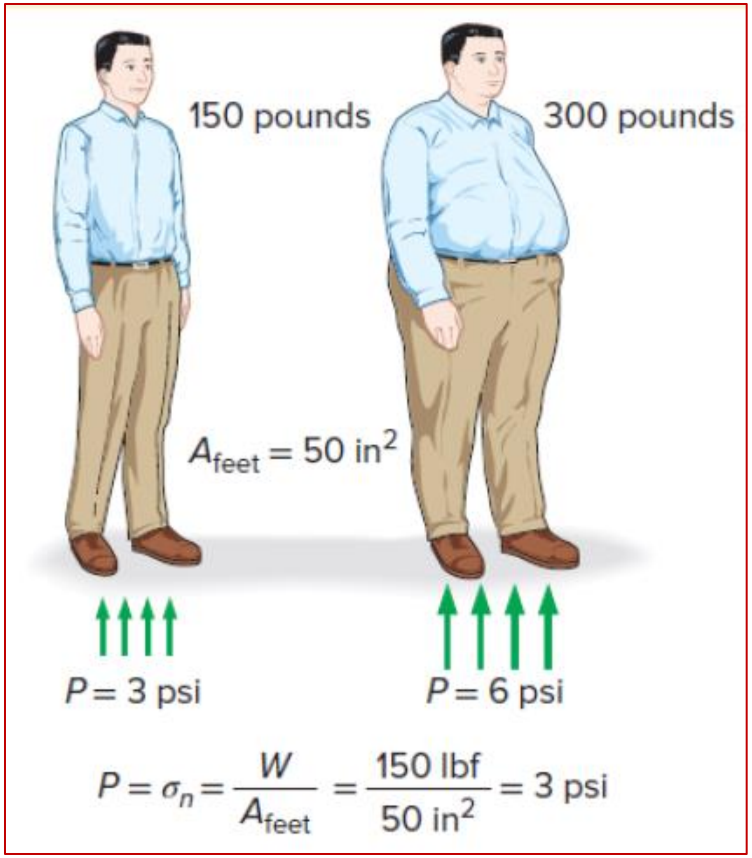


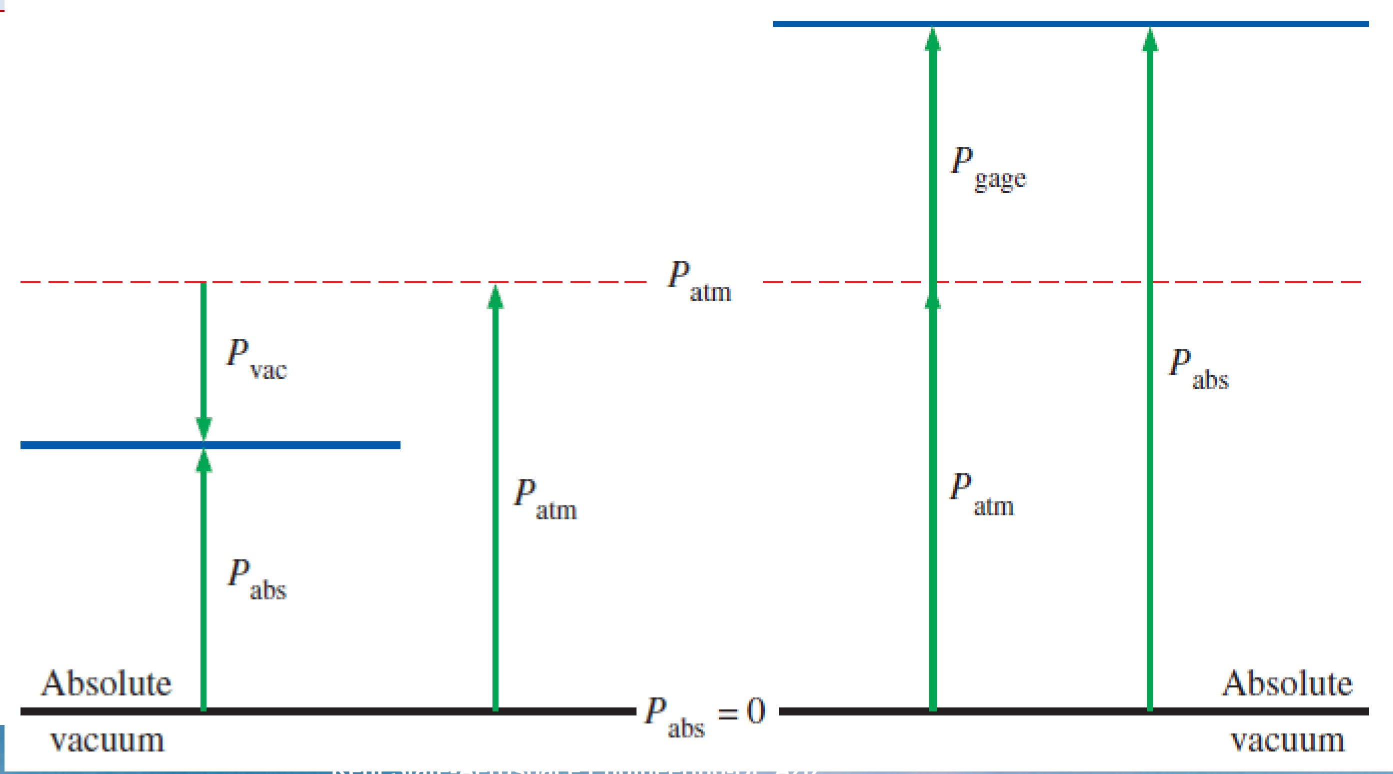
FIGURE 2-24

The normal stress(or "pressure") on the feet of a chubby person is much greater than on the feet of a slim person.

2-7 PRESSURE-1

- **Absolute pressure:** The actual pressure at a given position. It is measured relative to absolute vacuum (i.e., absolute zero pressure).
- **Gage pressure:** The difference between the absolute pressure and the local atmospheric pressure. Most pressure-measuring devices are calibrated to read zero in the atmosphere, and so they indicate gage pressure.
- **Vacuum pressures:** Pressures below atmospheric pressure.

Throughout this text, the pressure ***P*** will denote ***absolute pressure*** unless specified otherwise.



EXAMPLE 2–2 Absolute Pressure of a Vacuum Chamber

A vacuum gage connected to a chamber reads 5.8 psi at a location where the atmospheric pressure is 14.5 psi. Determine the absolute pressure in the chamber.

SOLUTION

The gage pressure of a vacuum chamber is given. The absolute pressure in the chamber is to be determined.

Analysis

The absolute pressure is easily determined from **Eq. 2–13** to be

$$P_{abs} = P_{atm} - P_{vac} = 14.5 - 5.8 = \mathbf{8.7\ psi}$$

Discussion

Note that the *local* value of the atmospheric pressure is used when determining the absolute pressure.

Variation of Pressure with Depth

$$\Delta P = P_2 - P_1 = \rho g \, \Delta z = \gamma_s \Delta z$$

$\Delta P = P_{atm} + \rho g h$ or $P_{gage} = \rho g h$

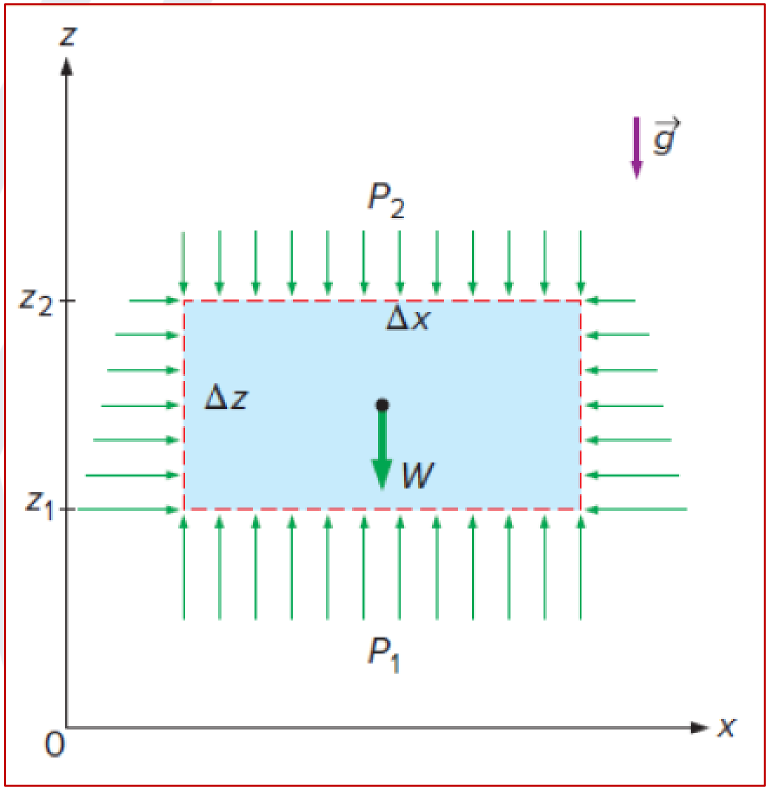


FIGURE 2-26

Free-body diagram of a rectangular fluid element in equilibrium.

When the variation of density with elevation is known.

$$\Delta P = P_2 - P_1 = -\int_1^2 \rho g \, \boldsymbol{d}z$$

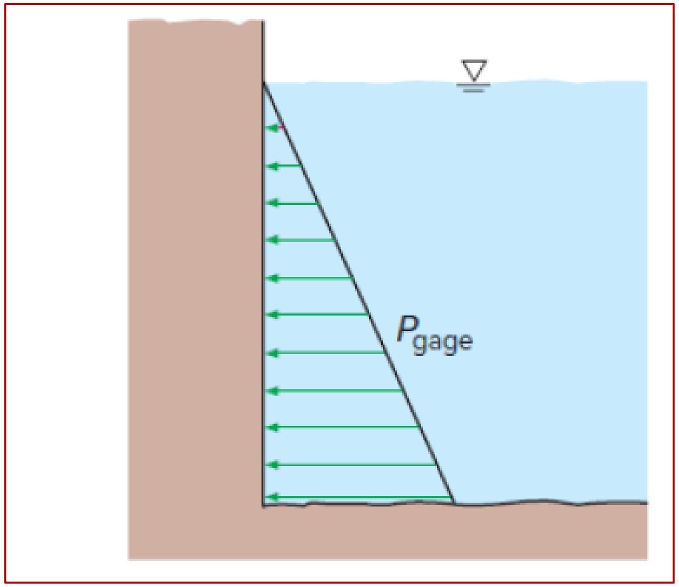


FIGURE 2-25

The pressure of a fluid at rest increases with depth (as a result of added weight)

Variation of Pressure with Depth-1

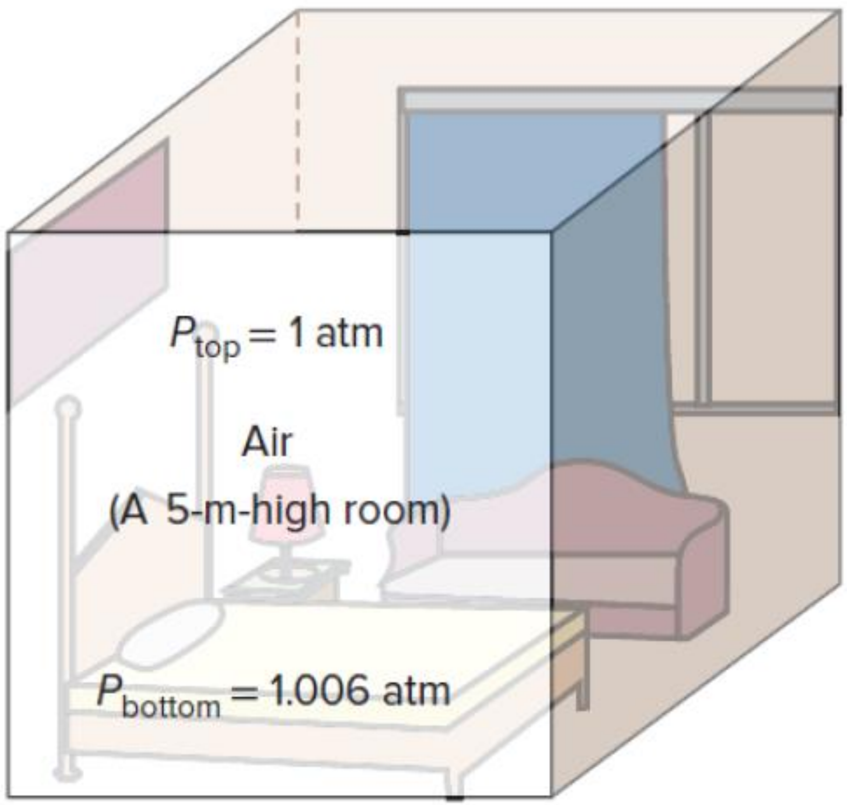


FIGURE 2-27

In a room filled with a gas, the variation of pressure with height is negligible.

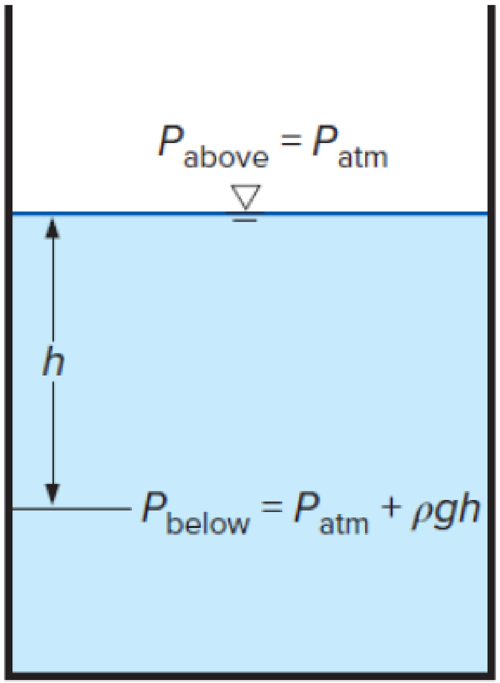


FIGURE 2-28

Pressure in a liquid at rest increases linearly with distance from the free surface.

Variation of Pressure with Depth-2

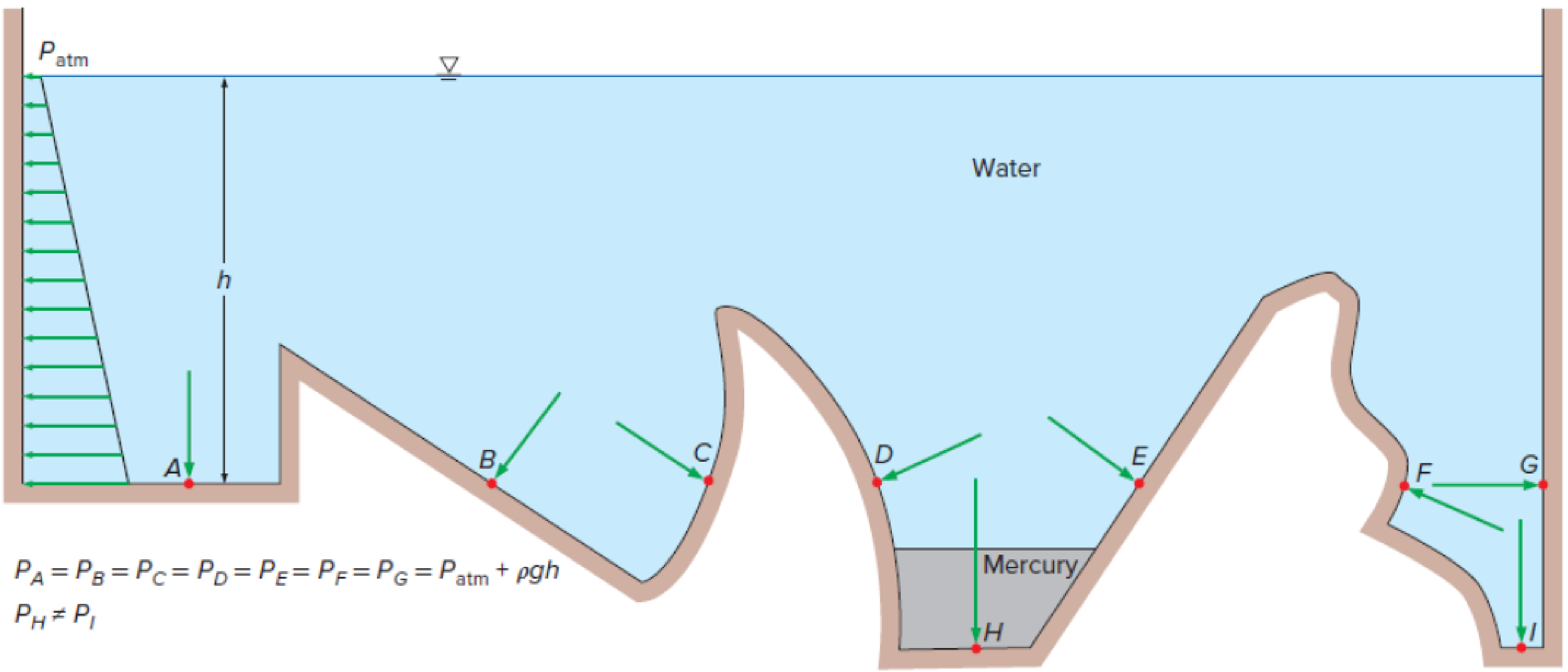


FIGURE 2-29

Under hydrostatic conditions, the pressure is the same at all the points on a horizontal plane in a given in a given fluid regardless of geometry, provided that the points are interconnected by the same fluid.

EXAMPLE 2–3 Measuring Atmospheric Pressure with a Barometer

Determine the atmospheric pressure at a location where the barometric reading is 740 mmHg and the gravitational acceleration is $g = 9.805$ m/s^2. Assume the temperature of mercury to be 10°C, at which its density is 13,570 kg/m^3.

SOLUTION

The barometric reading at a location in height of mercury column is given. The atmospheric pressure is to be determined.

Assumptions

The temperature of mercury is assumed to be 10°C.

Properties

The density of mercury is given to be 13,570 kg/m^3.

Analysis

From **Eq. 2–20**, the atmospheric pressure is determined to be

$$\begin{aligned} P_{atm} &= \rho g h \\ &= (13{,}570\ \mathrm{kg/m^3})(9.805\ \mathrm{m/s^2})(0.740\ \mathrm{m})\left(\frac{1\ \mathrm{N}}{1\ \mathrm{kg{\cdot}m/s^2}}\right)\left(\frac{1\ \mathrm{kPa}}{1000\ \mathrm{N/m^2}}\right) \\ &= \mathbf{98.5\ kPa} \end{aligned}$$

Discussion

Note that density changes with temperature, and thus this effect should be considered in calculations.

EXAMPLE 2–4 Gravity Driven Flow from an IV Bottle

Intravenous infusions usually are driven by gravity by hanging the fluid bottle at sufficient height to counteract the blood pressure in the vein and to force the fluid into the body (**Fig. 2–34**). The higher the bottle is raised, the higher the flow rate of the fluid will be. (*a*) If it is observed that the fluid and the blood pressures balance each other when the bottle is 1.2 m above the arm level, determine the gage pressure of the blood. (*b*) If the gage pressure of the fluid at the arm level needs to be 20 kPa for sufficient flow rate, determine how high the bottle must be placed. Take the density of the fluid to be 1020 kg/m^3.

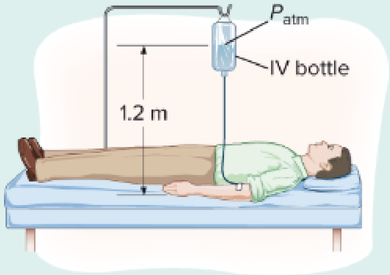


FIGURE 2–34
Schematic for **Example 2–4**.

SOLUTION

It is given that an IV fluid and the blood pressures balance each other when the bottle is at a certain height. The gage pressure of the blood and elevation of the bottle required to maintain flow at the desired rate are to be determined.

Assumptions

1 The IV fluid is incompressible. **2** The IV bottle is open to the atmosphere.

Properties

The density of the IV fluid is given to be ρ = 1020 kg/m^3.

Analysis

(*a*) Noting that the IV fluid and the blood pressures balance each other when the bottle is 1.2 m above the arm level, the gage pressure of the blood in the arm is simply equal to the gage pressure of the IV fluid at a depth of 1.2 m,

$$\begin{aligned} P_{\text{gage, arm}} &= P_{\text{abs}} - P_{\text{atm}} = \rho g h_{\text{arm - bottle}} \\ &= (1020 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(1.20 \text{ m})\left(\frac{1 \text{ kN}}{1000 \text{ kg}\cdot\text{m/s}^2}\right)\left(\frac{1 \text{ kPa}}{1 \text{ kN/m}^2}\right) \\ &= \mathbf{12.0 \text{ kPa}} \end{aligned}$$

(*b*) To provide a gage pressure of 20 kPa at the arm level, the height of the surface of the IV fluid in the bottle from the arm level is again determined from $P_{\text{gage, arm}} = \rho g h_{\text{arm – bottle}}$ to be

$$\begin{aligned} h_{\text{arm - botttle}} &= \frac{P_{\text{gage, arm}}}{\rho g} \\ &= \frac{20 \text{ kPa}}{(1020 \text{ kg/m}^3)(9.81 \text{ m/s}^2)}\left(\frac{1000 \text{ kg}\cdot\text{m/s}^2}{1 \text{ kN}}\right)\left(\frac{1 \text{ kN/m}^2}{1 \text{ kPa}}\right) \\ &= \mathbf{2.00 \text{ m}} \end{aligned}$$

Discussion

Note that the height of the reservoir can be used to control flow rates in gravity-driven flows. When there is flow, the pressure drop in the tube due to frictional effects also should be considered. For a specified flow rate, this requires raising the bottle a little higher to overcome the pressure drop.

Variation of Pressure with Depth-3

Pascal's law: **The pressure applied to a confined fluid increases the pressure throughout by the same amount.**

$$P_1 = P_2 \ \rightarrow \frac{F_1}{A_1} = \frac{F_2}{A_2} \rightarrow \frac{F_2}{F_1} = \frac{A_2}{A_1}$$

The area ratio A_2/A_1 is called the *ideal mechanical advantage* of the hydraulic lift.

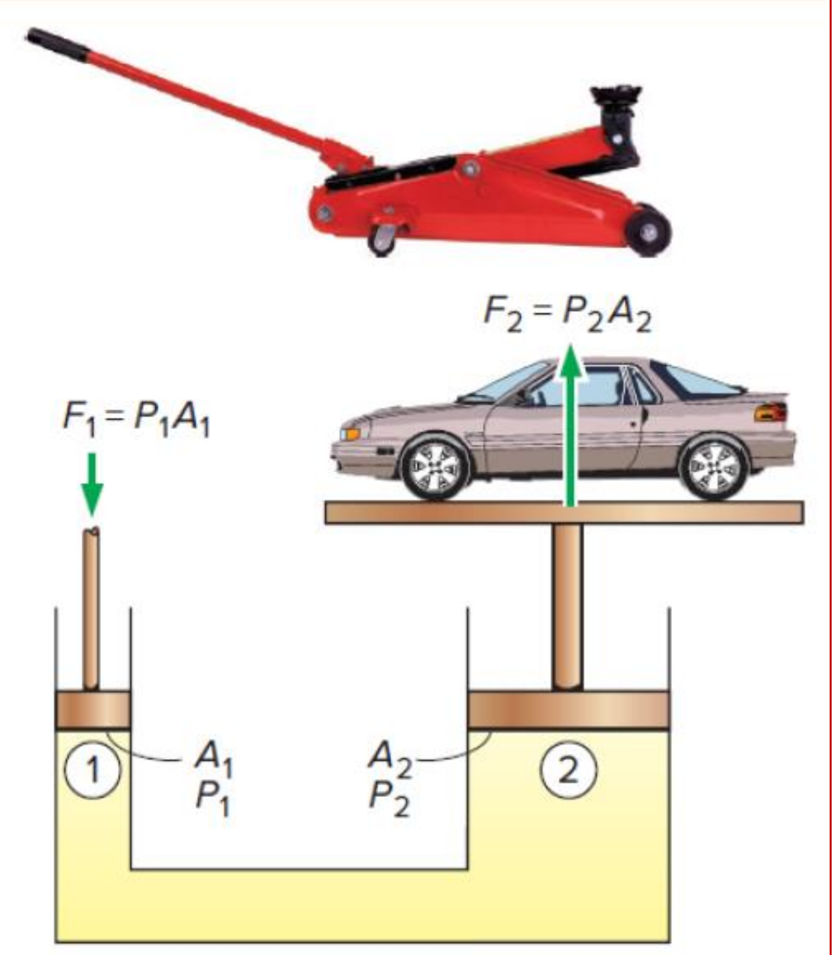


FIGURE 2-30

Lifting of a large weight by a small force by the application of Pascal's law. A common example is a hydraulic jack.

2-8 PRESSURE MEASUREMENT DEVICES

The Barometer

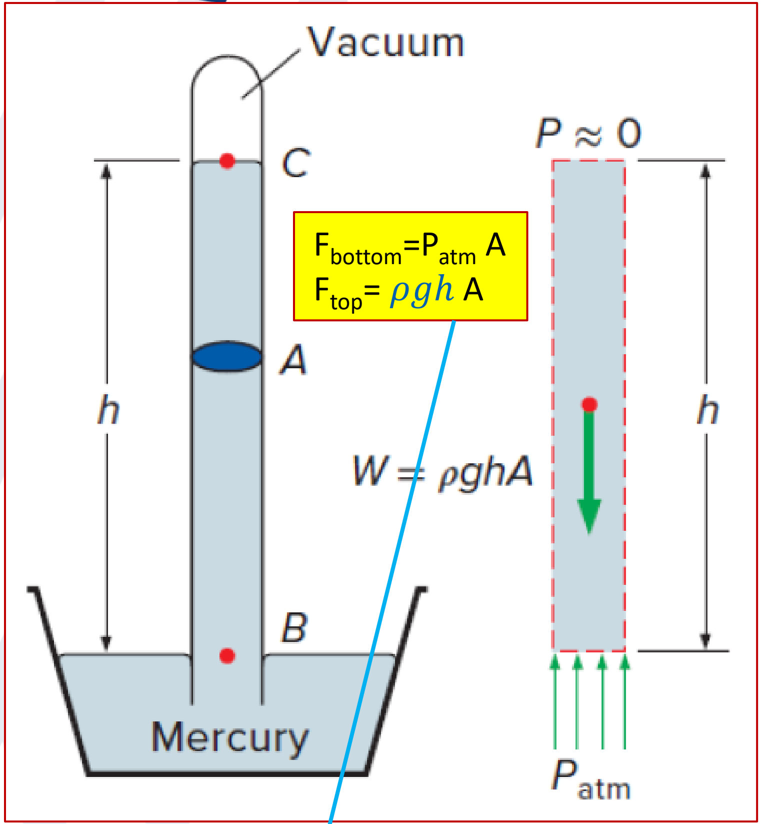


FIGURE 2-31
The basic barometer.

$$P_{atm} = \rho g h$$

- **Atmospheric pressure is measured by a device called a *barometer;* thus, the atmospheric pressure is often referred to as the *barometric pressure*.**
- **A frequently used pressure unit is the *standard atmosphere*, which is defined as the pressure produced by a column of mercury 760 mm in height at 0°C (ρ_{Hg} = 13,595 kg/m^3) under standard gravitational acceleration (g = 9.807 m/s^2).**

Torricelli an Italian scientist proved that atmospheric pressure can be measured by inverting a mercury filled tube into a mercury container that is open to the atmosphere.

2-8 PRESSURE MEASUREMENT DEVICES-1

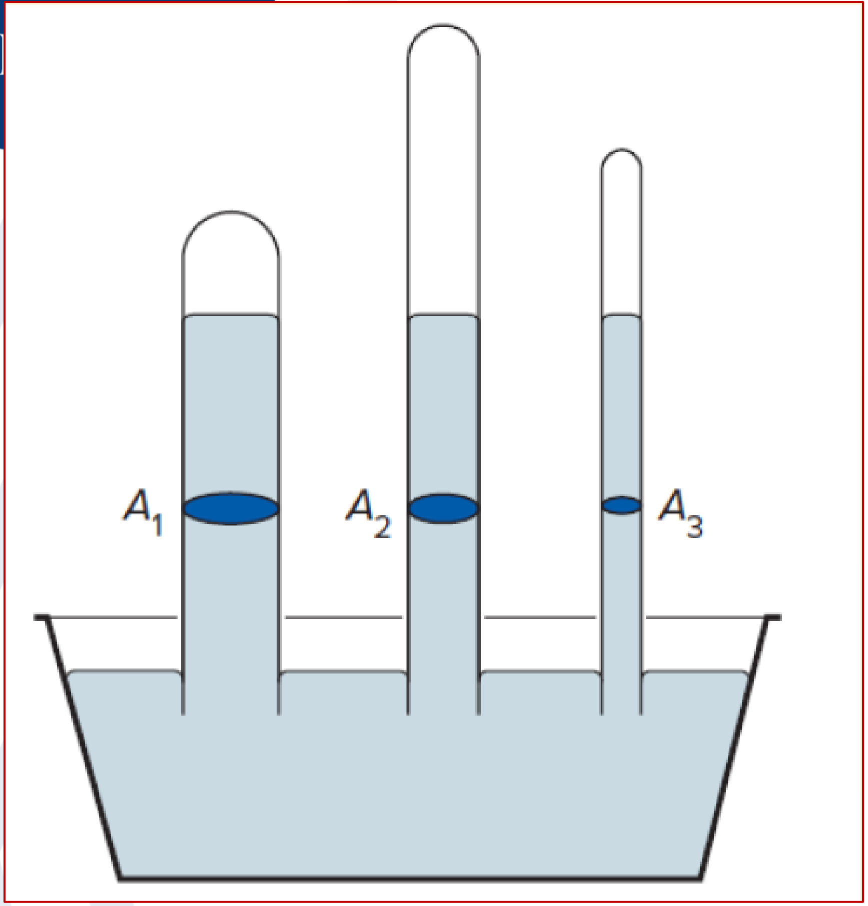


FIGURE 2-32

The length or the cross-sectional area of the tube has no effect on the height of the fluid column of a barometer, provided that the tube diameter is large enough to avoid surface tension (capillary) effects.

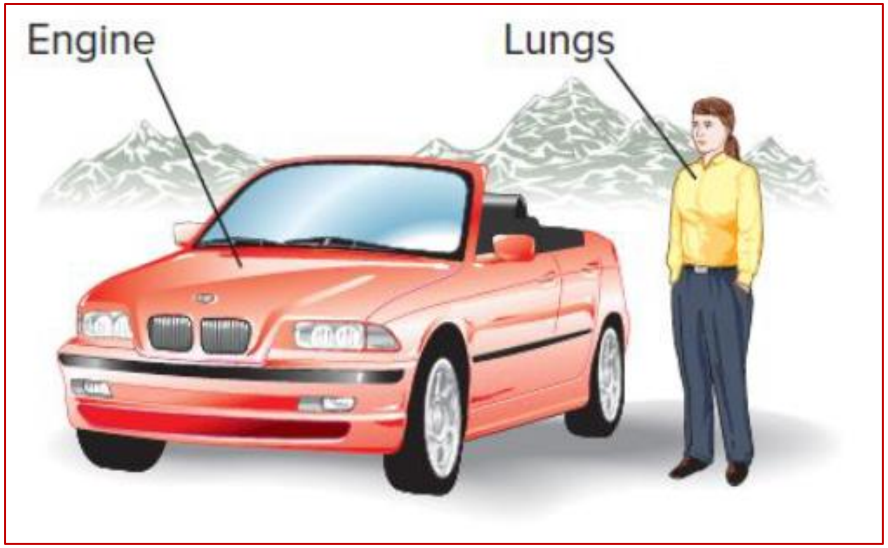


FIGURE 2-33

At high altitudes, a car engine generates less power and a person gets less oxygen because of the lower density of air.

The Manometer

FIGURE 2-37
A simple U-tube manometer, with high pressure applied to the right side.

It is commonly used to measure small and moderate pressure differences. A manometer contains one or more fluids such as mercury, water, alcohol, or oil.

$$P_2 = P_{atm} + \rho g h$$

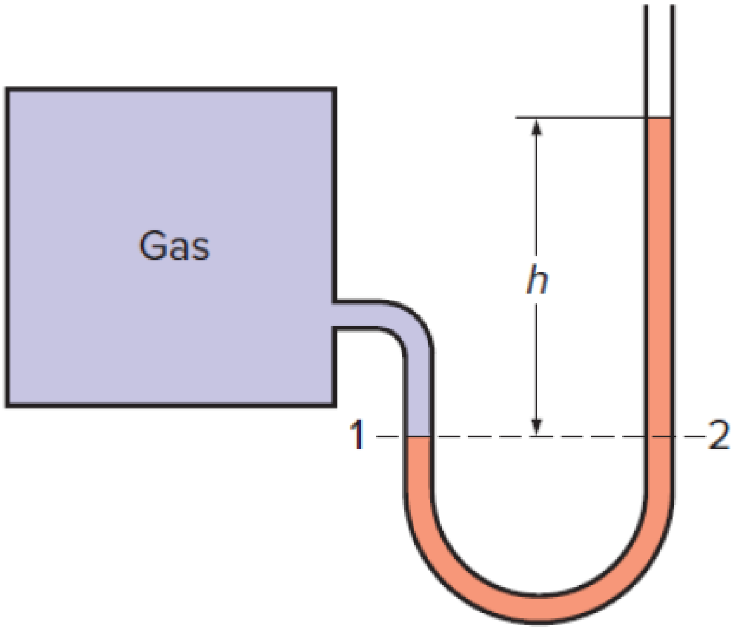


FIGURE 2-38
The basic manometer.

EXAMPLE 2–6 **Measuring Pressure with a Manometer**

A manometer is used to measure the pressure of a gas in a tank. The fluid used has a specific gravity of 0.85, and the manometer column height is 55 cm, as shown in Fig. 2–39. If the local atmospheric pressure is 96 kPa, determine the absolute pressure within the tank.

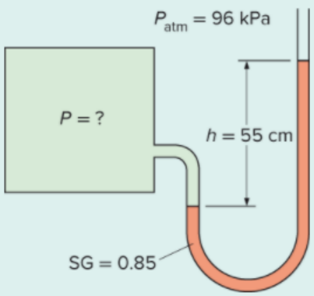


FIGURE 2–39
Schematic for Example 2–6.

SOLUTION

The reading of a manometer attached to a tank and the atmospheric pressure are given. The absolute pressure in the tank is to be determined.

Assumptions

The density of the gas in the tank is much lower than the density of the manometer fluid.

Properties

The specific gravity of the manometer fluid is given to be 0.85. We take the standard density of water to be 1000 kg/m^3.

Analysis

The density of the fluid is obtained by multiplying its specific gravity by the density of water,

$$\rho = \text{SG}\,(\rho H_2O) = (0.85)(1000\ \text{kg/m}^3) = 850\ \text{kg/m}^3$$

Then from Eq. 2–21,

$$P = P_{\text{atm}} + \rho g h$$

$$= 96\ \text{kPa} + (850\ \text{kg/m}^3)(9.81\ \text{m/s}^2)(0.55\ \text{m})\left(\frac{1\ \text{N}}{1\ \text{kg·m/s}^2}\right)\left(\frac{1\ \text{kPa}}{1000\ \text{N/m}^2}\right)$$

$$= \mathbf{100.6\ kPa}$$

Discussion

Note that the gage pressure in the tank is 4.6 kPa.

The Manometer-1

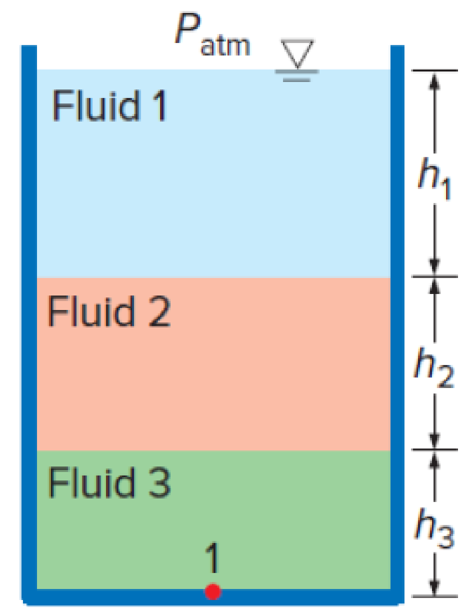


FIGURE 2-40

In stacked-up fluid layers at rest, the pressure change across each fluid layer of density ρ and height h is $\rho g h$.

$$P_{atm} + \rho_1 g h_1 + \rho_2 g h_2 + \rho_3 g h_3 = P_1$$

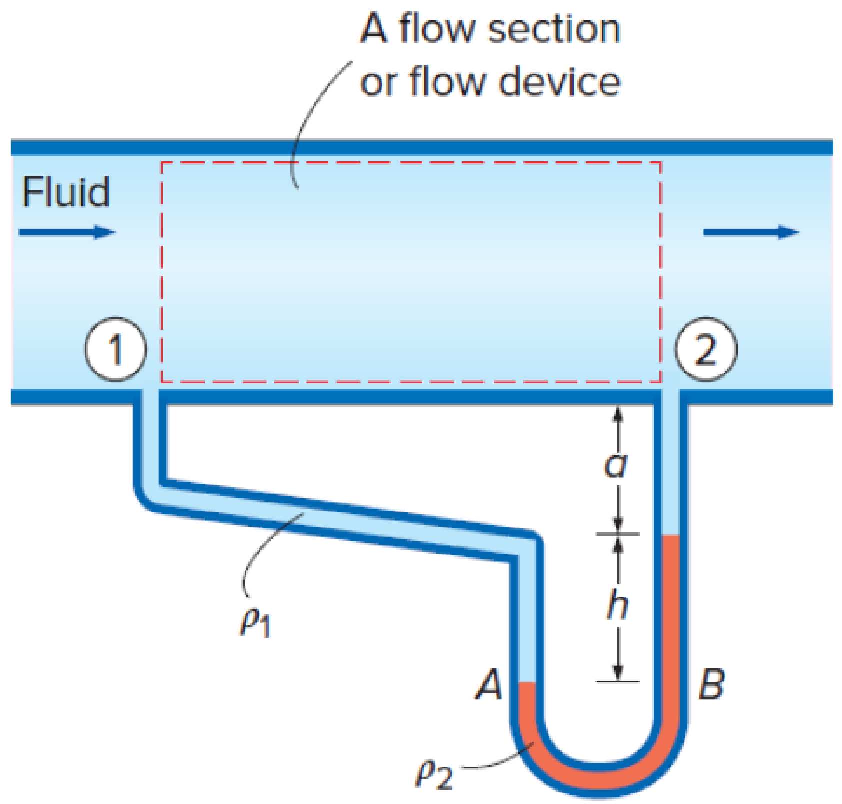


FIGURE 2-41

Measuring the pressure drop across a flow section or a flow device by a differential manometer.

$$P_1 + \rho_1 g(a + h) - \rho_2 g h - \rho_1 g a = P_2$$

$$P_1 - P_2 = (\rho_2 - \rho_1) g h$$

EXAMPLE 2–7 Measuring Pressure with a Multifluid Manometer

The water in a tank is pressurized by air, and the pressure is measured by a multifluid manometer as shown in Fig. 2–42. The tank is located on a mountain at an altitude of 1400 m where the atmospheric pressure is 85.6 kPa. Determine the air pressure in the tank if h_1 = 0.1 m, h_2 = 0.2 m, and h_3 = 0.35 m. Take the densities of water, oil, and mercury to be 1000 kg/m^3, 850 kg/m^3, and 13,600 kg/m^3, respectively.

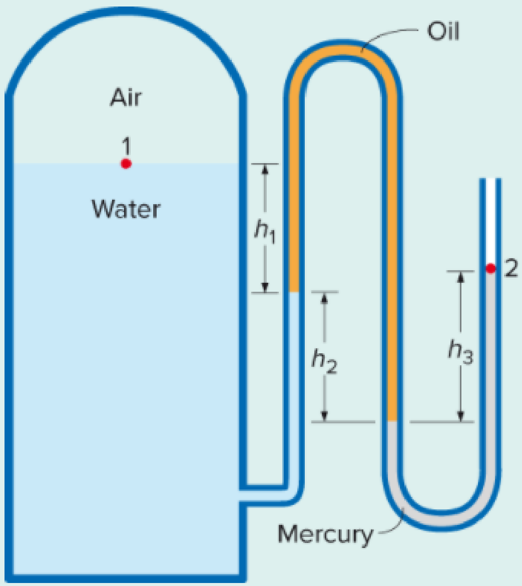


FIGURE 2–42
Schematic for Example 2–7; drawing not to scale.

SOLUTION

The pressure in a pressurized water tank is measured by a multifluid manometer. The air pressure in the tank is to be determined.

Assumption

The air pressure in the tank is uniform (i.e., its variation with elevation is negligible due to its low density), and thus we can determine the pressure at the air–water interface.

Properties

The densities of water, oil, and mercury are given to be 1000 kg/m^3, 850 kg/m^3, and 13,600 kg/m^3, respectively.

Analysis

Starting with the pressure at point 1 at the air–water interface, moving along the tube by adding or subtracting the ρgh terms until we reach point 2, and setting the result equal to P_{atm} since the tube is open to the atmosphere gives

$$P_1 + \rho_{water}\, gh_1 + \rho_{oil}\, gh_2 - \rho_{mercury} gh_3 = P_2 = P_{atm}$$

Solving for P_1 and substituting,

$$\begin{aligned}
P_1 &= P_{atm} - \rho_{water}\, gh_1 - \rho_{oil}\, gh_2 + \rho_{mercury}\, gh_3 \\
&= P_{atm} + g(\rho_{mercury} h_3 - \rho_{water} h_1 - \rho_{oil} h_2) \\
&= 85.6 \text{ kPa} + (9.81 \text{ m/s}^2)[(13{,}600 \text{ kg/m}^3)(0.35 \text{ m}) - (1000 \text{ kg/m}^3)(0.1 \text{ m}) \\
&\quad - (850 \text{ kg/m}^3)(0.2 \text{ m})]\left(\frac{1 \text{ N}}{1 \text{ kg·m/s}^2}\right)\left(\frac{1 \text{ kPa}}{1000 \text{ N/m}^2}\right) \\
&= \mathbf{130 \text{ kPa}}
\end{aligned}$$

Other Pressure Measurement Device

- **Bourdon tube:** Consists of a hollow metal tube bent like a hook whose end is closed and connected to a dial indicator needle.
- **Pressure transducers:** Use various techniques to convert the pressure effect to an electrical effect such as a change in voltage, resistance, or capacitance.
- Pressure transducers are smaller and faster, and they can be more sensitive, reliable, and precise than their mechanical counterparts.

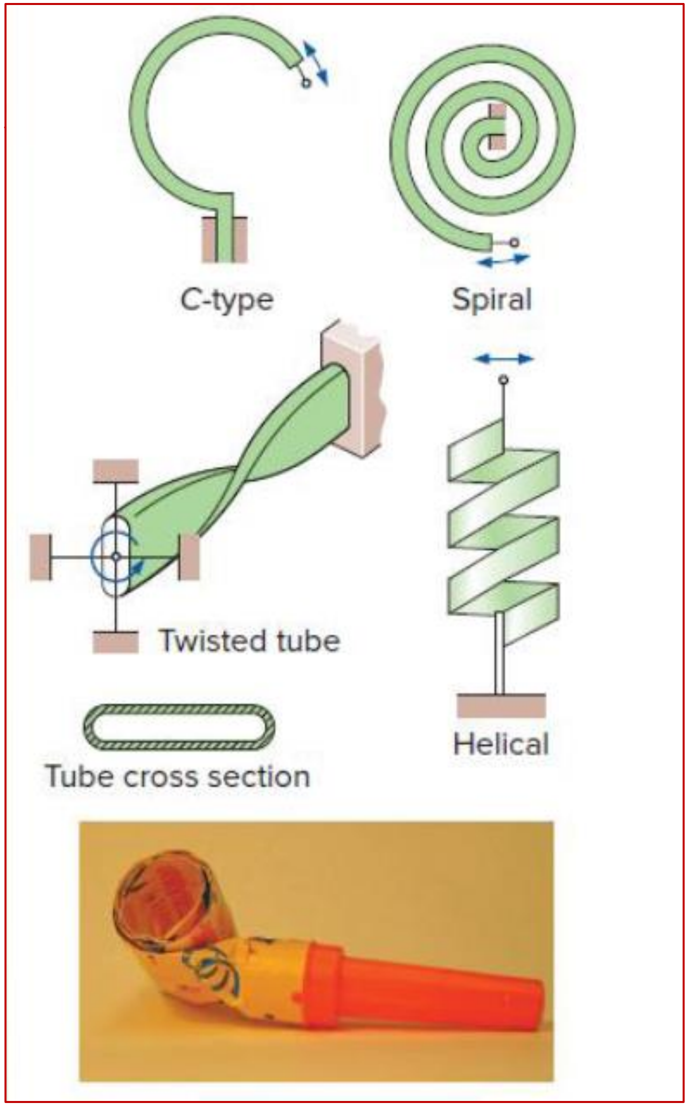


FIGURE 2-43
Various types of Bourdon tubes used to measure pressure. They work on the same principle as party noise-makers (bottom photo) due to the flat tube cross section.

Other Pressure Measurement Device

- **Strain-gage pressure transducers:** Work by having a diaphragm deflect between two chambers open to the pressure inputs.
- **Piezoelectric transducers:** Also called **solid-state pressure transducers,** work on the principle that an electric potential is generated in a crystalline substance when it is subjected to mechanical pressure.

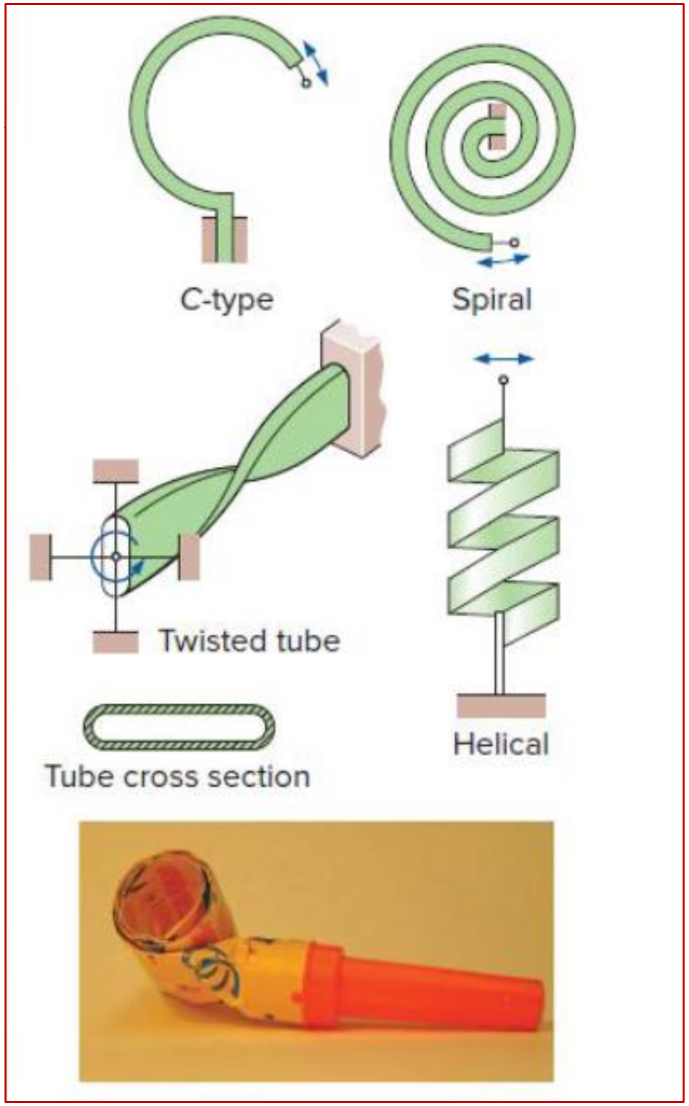


FIGURE 2-43

Various types of Bourdon tubes used to measure pressure. They work on the same principle as party noise-makers (bottom photo) due to the flat tube cross section.

Other Pressure Measurement Devices-1

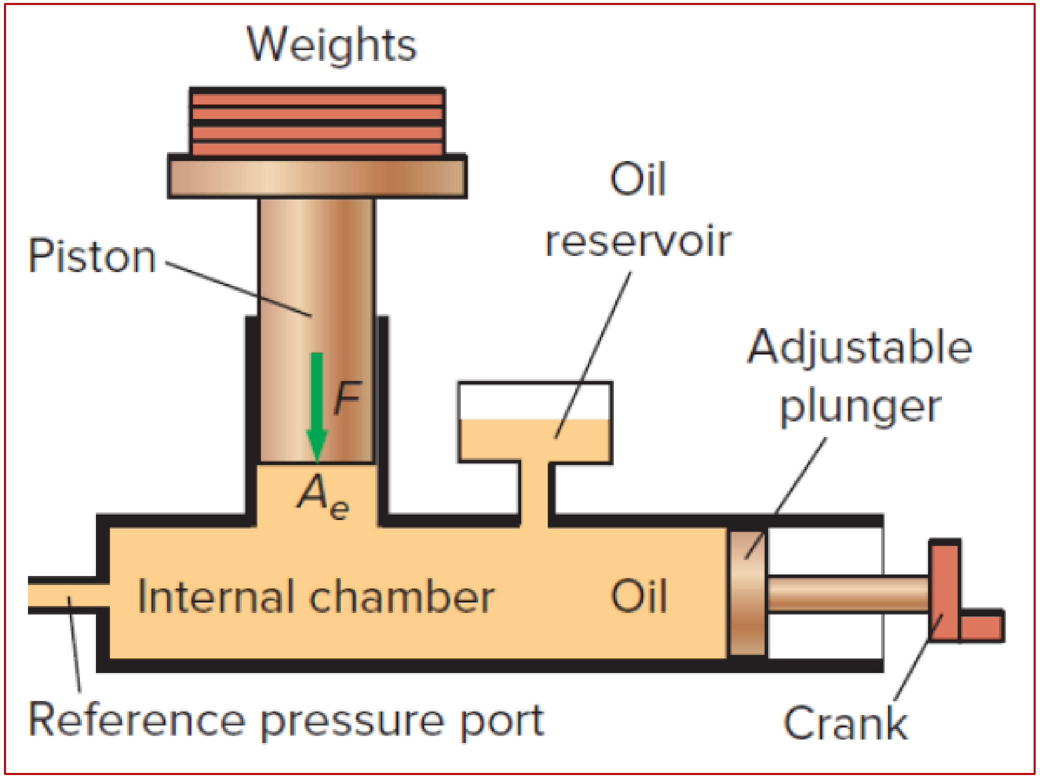


FIGURE 2-44

A deadweight tester is able to measure extremely high pressures (up to 10,000 psi in some applications).

Summary

- **Systems and control volumes**
- **Properties of a system**
- **Density and specific gravity**
- **State and equilibrium**
- **Processes and cycles**
  - The steady-flow process
- **Temperature and the zeroth law of thermodynamics**
  - Temperature scales
  - ITS-90
- **Pressure**
  - Variation of pressure with depth
- **Pressure Measurement Devices**
  - The Barometer
  - The Manometer
  - Other Pressure Measurement Devices